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The Multimeter

Current Electricity

THE MULTIMETER

A Module on Current Electricity

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The Multimeter

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INTRODUCTION

Have you ever measured voltage or current, using a voltmeter or ammeter? If not, the material presented in this module will be new to you, but you need not worry that it will be over your head. The material is meant for the beginner, and previous knowledge of physical principles or electrical measurements is not a requirement. Those of you who are already familiar with the use of voltmeters and ammeters are a step ahead, but you may not know the physics behind meter measurements. A more thorough understanding of a measurement begins with understanding the physical principles involved. This is precisely what we hope this module can do for you.

The general goal of the module is to help you to learn the use and the principles of operation of the *multimeter*. In the process you will learn how to analyze some common electrical circuits. As a result, you will be able to understand the manufacturers' specifications for multimeters.

SECTION A

GLOSSARY OF TERMS AND SYMBOLS

In discussions of electricity, several terms and symbols are commonly used. The following list includes some of those which appear most frequently. Many of them may be already familiar to you. The others should become familiar as you proceed through the module. You might find it helpful to scan through the list to familiarize yourself with the terms, but you should be sure to return to it whenever you come across a term you don't understand in the text. Don't be disturbed if you do not understand all of the terms the first time you read the definitions; a real understanding will develop with repeated use.

Electric Current (symbol I). The flow of electric charge. It is measured in *amperes* (symbol A). The flow rate may be compared with that of water flowing in a river; the greater the flow rate, the greater the current. (Note: To talk about "current flow" is redundant, since current means "a flow," but it is very commonly used, and we shall use it in this module to mean simply "current.")

Ammeter. An instrument for measuring electric current.

Electric Charge. This will not be used in the module, so we won't describe its properties in detail. In general, electric charges are such that they exert long-range, non-gravitational forces on each other.

Circuit. A closed path (or loop) through which a current can flow.

Conductor. A material, usually a metal such as copper, through which a current passes easily.

Insulator. A material, such as most plastics, through which a current does not pass easily.

Resistance (symbol R). Opposition to a current. It is measured in *ohms* (symbol Greek letter *omega*, Ω). Even good conductors, such as copper wire, offer some resistance to a current. Materials with greater resistance may be measured in kilohms ($1\ k\Omega = 10^3\ \Omega$) and megohms ($1\ M\Omega = 10^6\ \Omega$). Frequently these are abbreviated as *1 K* and *1 Meg*, respectively.

Resistor. A device which provides a designated amount of resistance. The value of a resistor may be specified by a color code (see Appendix A) or by a number printed on it.

Ohmmeter. An instrument for measuring resistance.

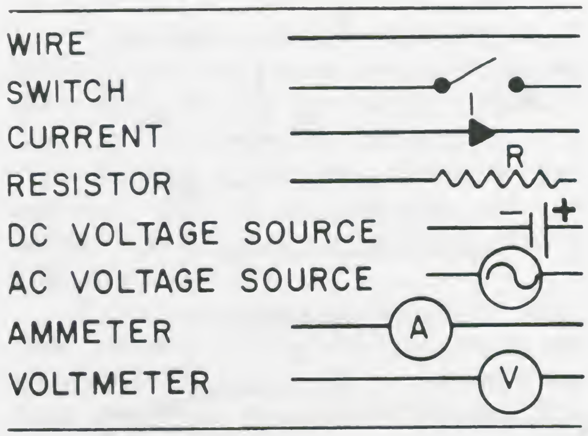
Voltage (symbol V). The voltage between two points in a circuit is the work required to push a charge from one of those points to the other, divided by the amount of charge pushed. Or, more briefly, it is work per unit charge. Voltage is measured in units of *volts* (V), and is also called *potential difference*. The voltage across a resistor is frequently called a *voltage drop*. Often, the voltages in an electronic circuit are measured between a point in the circuit and the circuit *ground* (usually the chassis box). Hence, the voltage at one end of a resistor may be 50 V above ground and at the other end 40 V, thus a voltage drop of 10 V is present.

Voltmeter. An instrument for measuring voltages, or potential differences.

Circuit Diagram. Also called a *schematic*. A way of representing an electrical circuit, using standard symbols for the various elements, as indicated in Table I.

Short-Circuit. A circuit which has little resistance. The current is very large when a short-circuit (a "short") occurs.

TABLE I



Open-Circuit. A circuit with a break in the electrical path so that no current flows.

Load. Any circuit component which uses power.

Power Supply. Also called a *voltage source*. A source of the energy required to move a charge around a circuit. It supplies the voltage (and current) for a circuit. A battery is an example of such a device.

Direct Current. Abbreviated as *DC*. This is a current which always flows in the same direction. A battery is a source of direct current (often redundantly called *DC current*) since it supplies DC voltage.

Alternating Current. Abbreviated as *AC*. This is a current which reverses its direction periodically. In the United States it usually alternates 120 times a second, or 60 complete cycles per second. AC voltages are usually supplied by generators in power plants.

Series Circuit. Circuit components are in *series* if all the current which flows through one must flow through the others. (See Figure 1A.)

Parallel Circuit

Circuit components are in *parallel* if the current divides, with part going through one branch and part through the other branch as in Figure 1B.

More on Resistance

The resistors shown in Figures 1A and 1B may be lamps, heaters, or other devices, but basically they are resistances. Resistors appear in every circuit presented in this module. You may wonder what they do and what they are used for. They play an important role in electrical applications and deserve much more discussion.

Resistances always convert electric energy into heat energy, and sometimes into light as well. The rate at which energy is converted is called the *power*. For lamps and heaters, the conversion of power provides something useful in the form of light or heat.

However we may not be interested in using the light or heat given off by a resistor. Instead, we may use the resistor to perform other functions. Two of the most useful of these are:

1. To control the amount of current or to *limit* the current in a circuit.

2. To produce known voltage drops in a circuit.

The power used by the resistor is lost in these cases. It is *dissipated* as heat. Such wasted power is tolerated as are power losses due to friction in mechanical systems. Fortunately, the amount of power lost is not too great in most applications.

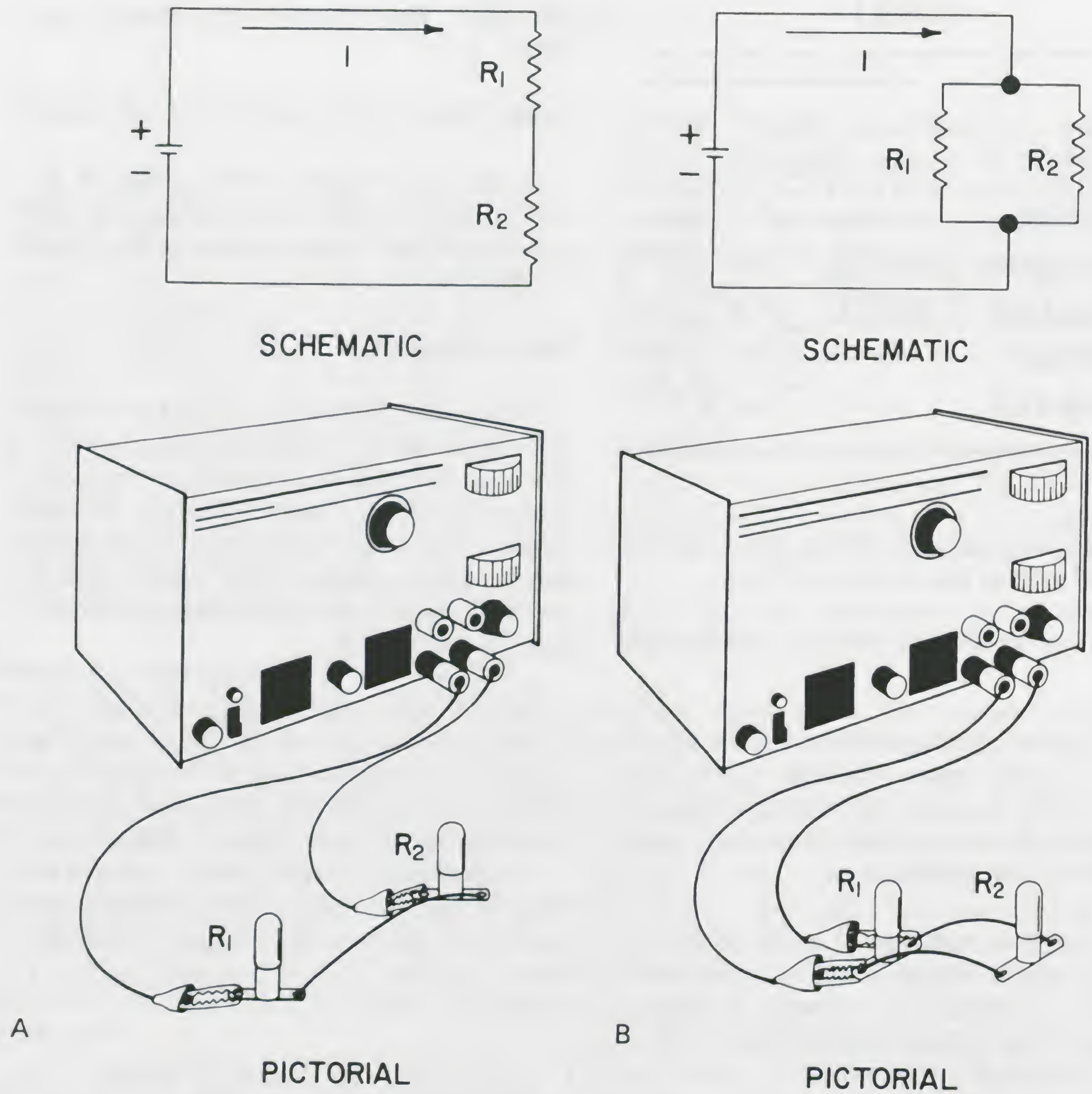


Figure 1A. The light bulbs, R_1 and R_2, are connected in series. Figure 1B. The light bulbs, R_1 and R_2, are connected in parallel.

Schematic Diagrams

A *schematic diagram,* or *schematic,* is a technician's "shorthand" which shows how to construct a given electrical circuit. Once you can recognize the schematic symbols (some are shown in Table I and Figure 4), you should be able to visualize how an actual circuit will look by studying its schematic. The value of a particular circuit element may be indicated either in a general way ($R\ \Omega$) or by a specific number (10 V).

Always remember to connect DC voltmeters and DC ammeters so that *current,* which flows out of the positive battery terminal, *flows into* the positive terminal of the meter. This means that the meter is connected into the circuit so that its positive terminal is closest (in the schematic sense) to the positive terminal of the battery. Always check meter connections by closing the switch *momentarily* and observing the meter deflection. If the needle deflects the "wrong" way, it is connected improperly and should be reversed.

THE MULTIMETER

In practice, electrical measurements of voltage, resistance, and current are frequently made with the same instrument, the *multimeter* or *VOM* (volt-ohm-milliammeter). It is a combination of voltmeter, ohmmeter, and ammeter. One of the objectives of this module is to acquaint you with this versatile measuring instrument.

A brief description of the type of multimeter you will be using with this module will be helpful. The core of the instrument is the *meter movement*, illustrated in Figure 2. The meter movement, pointer, and scale are called a *galvanometer*. The movement consists of a coil of wire mounted between the poles of a permanent magnet. Attached to the coil is a pointer. An electric current through the coil interacts with the magnet, causing the coil to rotate and the pointer to move. The amount of deflection, read on a *calibrated scale plate*, is an indication of the amount of current through the coil. The *range* of the meter movement is specified in terms of the amount of current which causes a *full-scale deflection* (takes the pointer all the way across the scale from its zero point). For example, a 100-microampere (μA) meter movement is one for which a current of 100 μA (1 μA = 10^{-6} A) will cause a full-scale deflection. By properly adding resistors to the galvanometer, it can be converted either into an ammeter or a voltmeter. Also, if a voltage source such as a small battery is added in the proper way, along with resistors, the instrument can be made into an ohmmeter. You will see how this can be accomplished after you have studied some simple circuits.

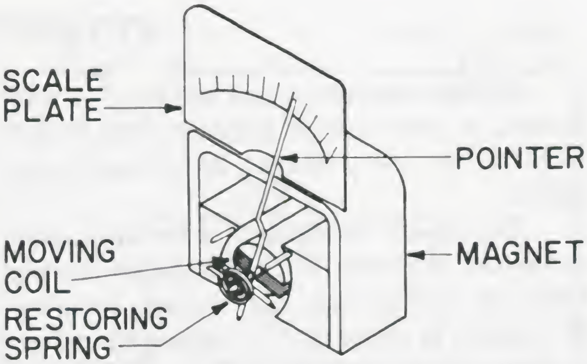


Figure 2. A galvanometer (meter movement).

An ammeter measures current, a voltmeter measures voltage, and an ohmmeter measures resistance. A multimeter can be operated as an ammeter, a voltmeter, or an ohmmeter by turning a selector switch or by using appropriate connections to select the desired function. Usually several ranges are provided for each function. The DC Volts function, for example, may be provided with scale ranges of 0 to 50 V, 0 to 100 V, and 0 to 500 V. The scale plates of some meters have two colors to simplify reading.

EXPERIMENT A-1. Circuits

In this experiment, you will learn to read meters, to draw circuit diagrams, and to put together, or *wire*, circuits from circuit diagrams.

The on-off function in a circuit is controlled by a *switch*. When the switch is *open* (off), no current can pass through it; when the switch is *closed* (on), it offers almost no resistance to the current.

Each of the following circuits provides an example of one important feature of a multimeter. However, don't expect a complete understanding now. That will come as you study the rest of the module.

Procedure

1. The circuit diagram in Figure 3 represents a circuit which already has been set up for you. Check the wiring to see how it is related to the diagram. Close switch S_1 and record the ammeter reading, I, with switch S_2 open and then with S_2 closed. When you are finished, open switch S_1. Record the values of R_1 and R_2. Later in the module you will see how this circuit can be used to change the range of an ammeter. You will also learn how to compute the correct value of R_2 to make an ammeter of any specified range.

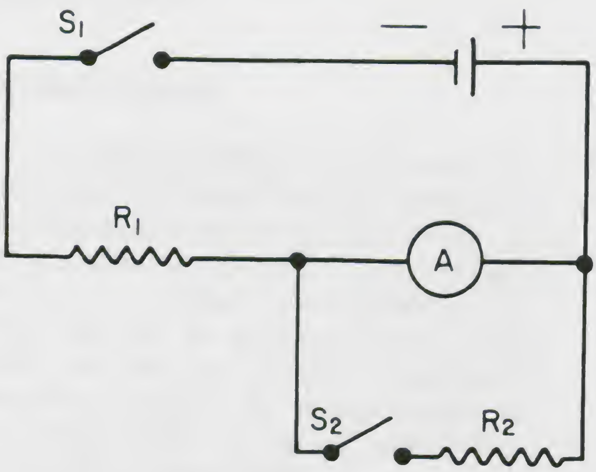


Figure 3.

2. Figure 4 shows the components of another circuit which has been wired for you. Examine this circuit and draw the appropriate lines in Figure 4 to complete the circuit diagram. Close switch S_1. On your data sheet record the current with S_2 open, and record both current and voltage with S_2 closed. When you are finished, open S_1. Record the value of R. Later in the module you will see that this provides an example of the way a meter affects the circuit to which it is connected.

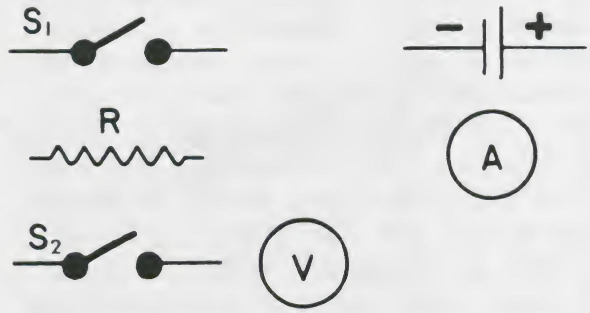


Figure 4.

3. Now identify the components needed to wire the circuit shown in Figure 5. Do the wiring. Then ask your instructor to check it for you *before* you close switch S_1. Record the voltmeter reading with S_2 open and with S_2 closed. Record the values of R_1 and R_2. When finished, disconnect the circuit. Later in the module you will see how this circuit can be used to change the range of a voltmeter.

4. The circuit diagram in Figure 6 represents another circuit which has been set up for you. Check the wiring to be sure that it agrees with the diagram. Close the switch. Record the meter readings and the values of the two resistors. The next section discusses how features of this circuit are used to convert an ammeter to a voltmeter.

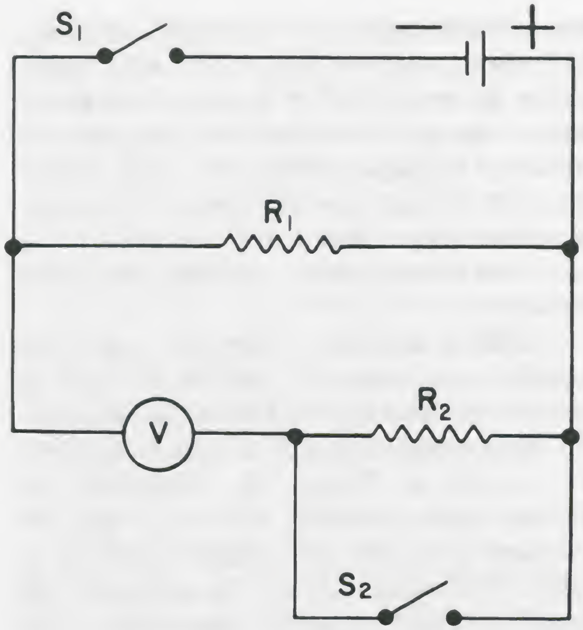


Figure 5.

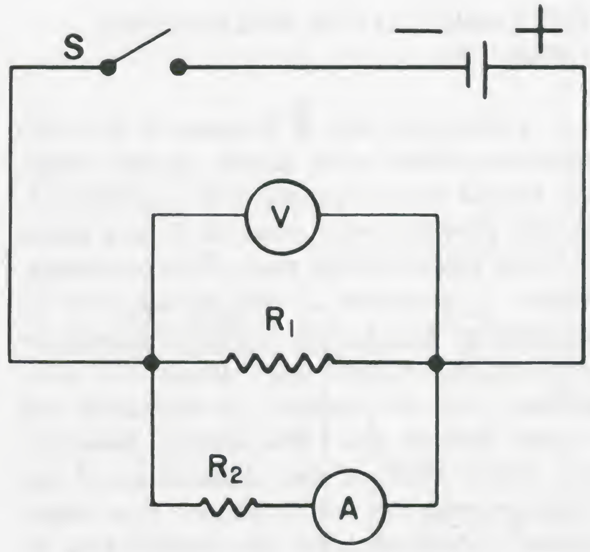


Figure 6.

FUNDAMENTALS OF MULTIMETER CIRCUITS

Experiment A-1 is designed to give you some experience with simple circuits which are related to the operation of a multimeter. It also provides some clues on how a single meter is made to do so many different things. Figure 7 is similar to the circuit used in Experiment A-1 (4). The voltmeter is wired to measure the voltage drop across the 1-kΩ resistor, and the ammeter is measuring the current through the 1-MΩ resistor. However, you might think of the combination of the ammeter and the 1-MΩ resistor as a *single device* as indicated by the dashed box in Figure 7. The black dots could represent the *terminals* of the device.

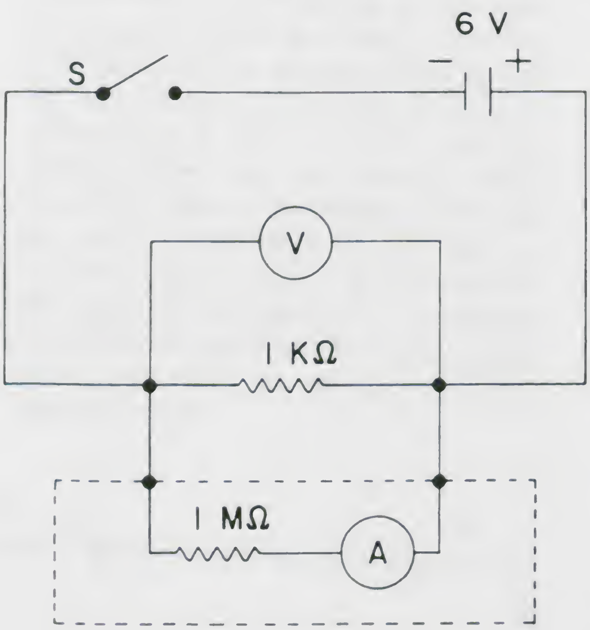


Figure 7.

The device in the box has the required features of a voltmeter. The deflection of the ammeter (which is proportional to the current through the 1-MΩ resistor) increases as the voltage across the terminals (which is the same as the voltage across the 1-kΩ resistor) increases. Also, the presence of the 1-MΩ resistor in series with the ammeter limits the amount of current which can pass through the meter. This means that the device does not *load* the circuit (it does not remove much power from the circuit). To make the device into a voltmeter, the ammeter scale must be *calibrated* to display volts instead of amperes. You will see how the calibration can be done experimentally. Thus, *an ammeter can be converted into a voltmeter by adding a series resistance.*

What if you have a voltmeter which will measure a maximum of only 10 V, but you need to measure 100 V? Figure 8 is similar to the circuit used in Step 3 of Experiment A-1. The circuit of Figure 8A corresponds to Figure 5 when switch S_2 is closed; Figure 8B corresponds to the case when switch S_2 is open. The meter labeled V_1 measures the "true" potential difference across the 1-K Ω

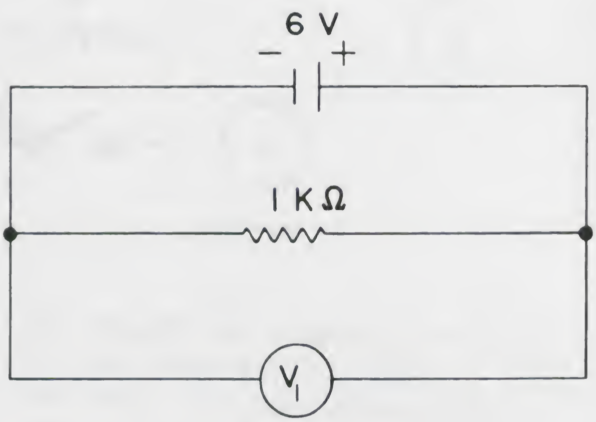


Figure 8A.

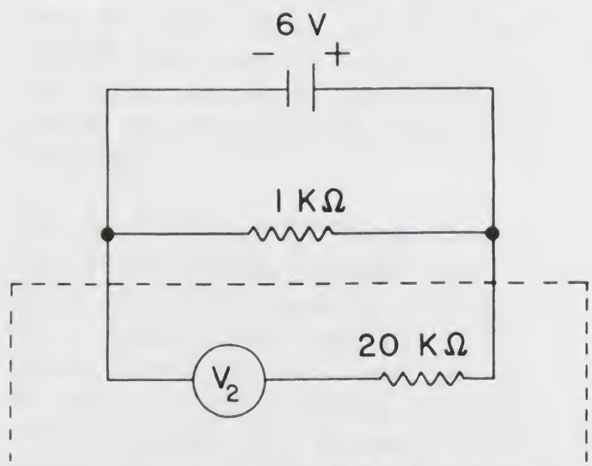


Figure 8B.

resistor. The meter labeled V_2 measures only a fraction of the actual voltage across the 1-kΩ resistor because the 20-kΩ resistor reduces the current flowing through the meter movement. But that's exactly the effect we need in order to increase the range of the meter. If it reads only one-tenth of the actual voltage, we have increased its range by a factor of ten. *The range of a voltmeter can be increased by adding a resistance, called a multiplier, in series.* When this is done, a new calibrated scale is required. The device enclosed by the dashed lines is then a voltmeter with an increased range.

In a slightly different way, one can change the range of an ammeter. Figure 9 is the same circuit used in Step 1 of Experiment A-1. Referring to Figure 3, Figure 9A corresponds to holding switch S_2 open and Figure 9B corresponds to holding S_2 closed. In Figure 9B the resistor connected in parallel with the ammeter is called a *shunt* resistor. The current in the 20-kΩ resistor divides when it reaches the branching point, with some going through the ammeter and some through the shunt. To measure a larger current through the 20-kΩ resistor, we need to cause the fraction passing through the shunt to increase. This is done by decreasing the resistance of the shunt resistor. Thus, the ammeter reads only a portion of the current and we need only to add a new calibrated scale to have an ammeter with a greater range. *The range of an ammeter can be increased by adding a resistor, called a shunt resistor, in parallel.*

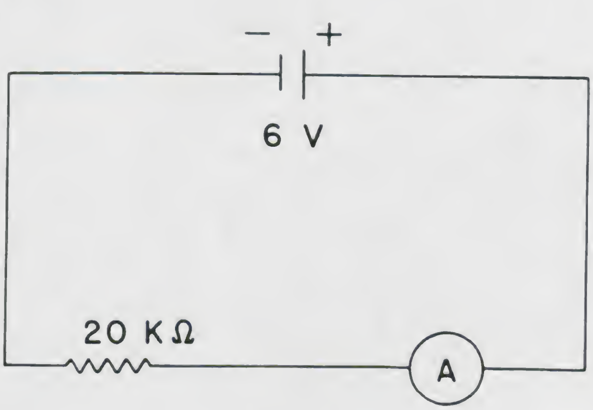


Figure 9A.

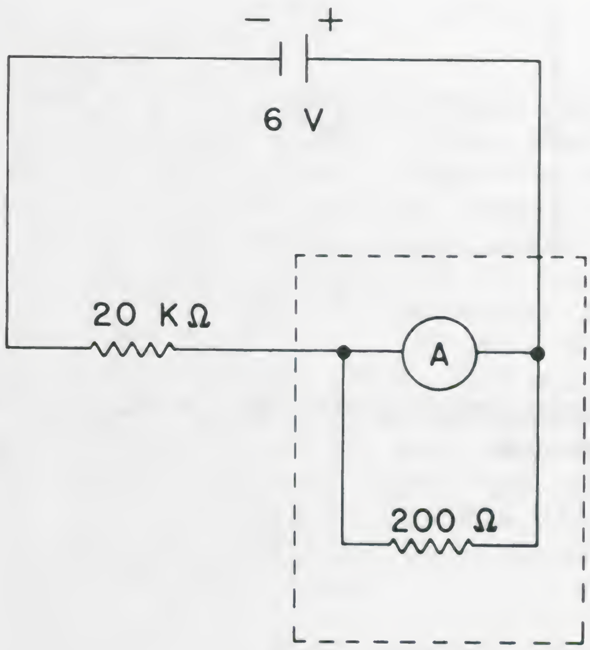


Figure 9B.

In most commercial multimeters, various series and shunt resistors are wired into the box. The appropriate ones are selected when you turn a switch to a designated position or plug the leads into the proper terminals. In the multimeter kit provided for later lab experiments, the proper resistors for the various functions and ranges are provided by plug-in units. These units are plugged into the terminals on the basic meter movement. The basic meter by itself is an ammeter which has full-scale deflection at 100 μA.

Example 1. For each of the circuits shown in Figure 10, state which meter will show the

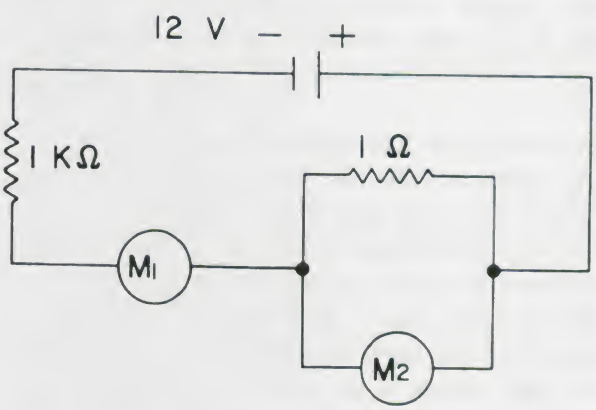


Figure 10A.

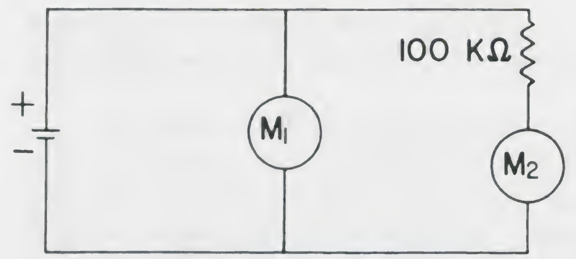


Figure 10B.

greater deflection, M_1 or M_2. The meters are identical.

Solution. In the circuit of Figure 10A, the current in the 1-Ω resistor and the current through meter M_2 combine to form the current through meter M_1. Thus, the current in meter M_1 is greater than that in meter M_2. Since the deflection of the meter movement is larger for larger currents, meter M_1 deflects more than meter M_2.

In the circuit of Figure 10B, the 100-kΩ resistor in series with meter M_2 causes the current in M_2 to be less than that in M_1. Therefore, M_1 deflects more than M_2.

EXPERIMENT A-2. Using the Multimeter

In this experiment, you will learn to use a multimeter to measure AC-voltage, DC-voltage, DC-current, and resistance. Since meter connections and adjustments are different for different types of multimeters, it is important that you consult the manufacturer's instructions to learn how to operate your particular multimeter. If you have trouble, ask your instructor for help.

Multimeters have certain basic features: Most multimeters are capable of measuring voltage, current, and resistance. The better ones have several ranges for each of these functions.

When there is no voltage or current input to the meter, the pointer rests at the zero-volt or zero-milliampere position at the left end of the scale plate. If the pointer is not on zero when the input is zero, its position should be corrected mechanically. Use a screwdriver to turn the zero-adjust screw at the base of the pointer until the pointer is "zeroed." Then the pointer should not require further readjustment for a long time. The ohms-adjust setting is a completely separate zero adjustment, which is electrically controlled and used only when the instrument is set to measure resistance. The procedure for this adjustment will be described later.

Safety Rules

For reasons of safety and protection of the instrument, follow these general rules when you use a multimeter:

1. *Be sure the instrument is set for the proper measuring function.* Using the multimeter's current- or resistance-measuring functions to measure voltages can damage the instrument.

2. *Do not touch the probe tips.* If one probe is connected to a high-voltage terminal and the tip of the other is touched by your fingers, you may receive a *severe* shock.

3. *Be sure the range is high enough.* When you measure voltage or current, always set the instrument to a range which is higher than the maximum voltage you plan to measure. This is necessary because a current through the meter which is larger than the current for full-scale deflection can cause the pointer to deflect violently. Such more-than-full-scale deflection can damage the pointer and ruin the meter. When in doubt, choose the highest range and work your way down. Then there is less chance the instrument will go off-scale and damage the pointer.

4. *Measure only isolated resistances.* When you measure resistance in a circuit, first turn the *power off*, then *isolate* (disconnect) the resistor from the rest of the circuit. This can be done by disconnecting one end of the resistor. If the resistor is not isolated, you may get an incorrect reading.

How to Measure AC-Line Voltage

Let's use the AC function of a commercial multimeter to measure AC line voltages. Line voltage is the voltage which appears at the wall outlet or receptacle. Typical line voltage values around the house are 120-V AC and 240-V AC. The higher voltage is needed to operate power equipment such as clothes driers, electric ranges, and some power tools. You can distinguish between the two types of receptacles by their physical appearances.

Be careful when working with line voltages. Electric shocks from line voltages are *dangerous*. Don't touch any metal parts. For safety reasons, all 240-V receptacles are provided with a third terminal which is *grounded*. In electrical terminology, a grounded circuit component, or *ground*, is connected directly to the earth by means of a water pipe, or some other suitably buried conductor. Prop-

erly grounding the case of a device effectively removes the shock hazard from that device. Older 120-V outlets have only two slots with no ground terminal. In all new construction, the National Electrical Code now requires 120-V outlets to have three-terminal grounding receptacles.

To measure the AC voltage, insert the test lead plugs into the appropriate jacks provided on the front panel of the multimeter. The instrument must be set to the AC volts measuring function and to a range above 240 V.

Carefully touch the meter probes to the terminals of either a 120-V or 240-V receptacle. Measure also the voltage at each terminal with respect to the third (grounding) terminal. Record your readings directly on the receptacles of Figure 11. What readings do you get when you interchange the probes? Discuss your results with your instructor and let him explain the wiring in each of the receptacles and the function of the grounding terminal.

How to Measure the DC Voltage of a Battery

The voltage supplied by a battery is called the *terminal voltage* of the battery. The terminal voltage for a "run-down" battery may appear normal if it is measured under conditions such that there is no current and therefore no energy drain on the battery. To determine whether or not a battery is "run-down," its terminal voltage must be measured

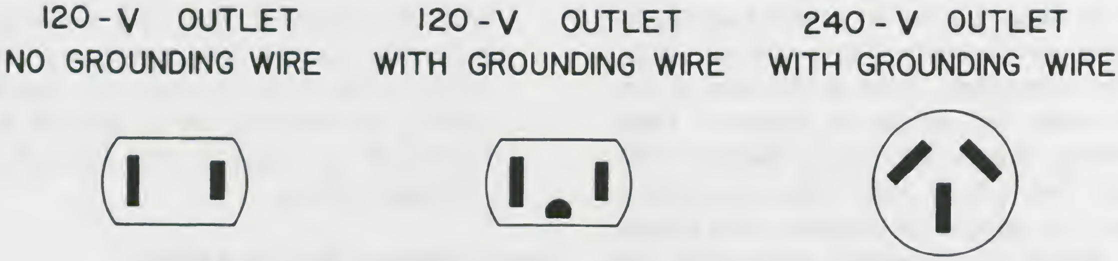


Figure 11.

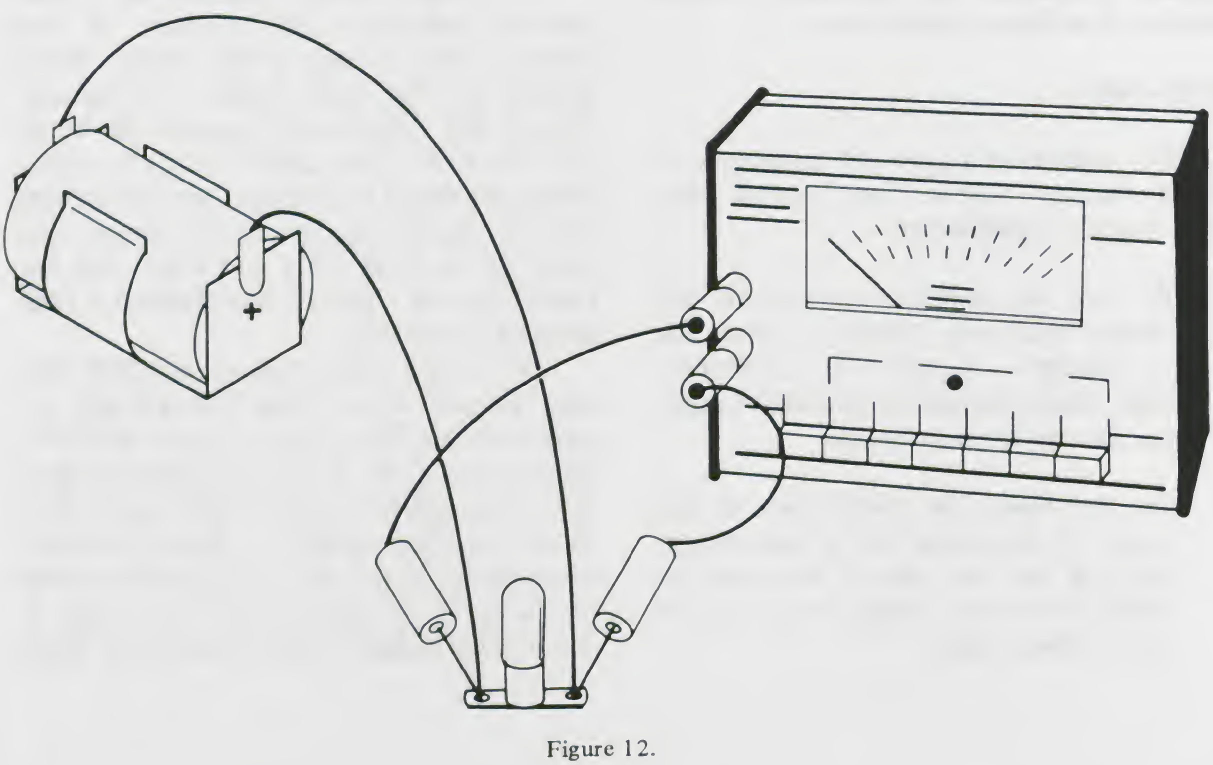


Figure 12.

while the battery is delivering a normal current. For the standard "D cell" used in flashlights, the terminal voltage is 1.5 V. If you connect a resistance of about 10 Ω (such as the filament of a flashlight bulb) across the battery, it will supply a small current through the resistance. The voltage drop across the resistance is equal to the terminal voltage of the battery.

Make the connections shown in Figure 12 and measure the voltage drop using the multimeter as a voltmeter. To be sure that the meter deflects in the right direction, you must connect the positive probe to the high-voltage end (+ end) of the resistance, and the negative probe to the low-voltage (−) end. In some complicated circuits, you may not be able to distinguish the high-voltage and low-voltage ends. In such a case, use the highest scale range available. Connect one probe to one of the measurement points. *Touch* the other probe to the second measurement point and observe the needle deflection. If the needle deflects positively, connect the second probe and change the scale as necessary to make the measurement. If the needle jumps off scale to the left of zero, you should interchange the probes.

If the battery voltage is measured to be 1.5 V and remains steady, the battery is probably in good condition. If the voltage decreases gradually, the battery is "run-down."

NOTE: To test a car battery (typically 12 V), measure the voltage between the battery terminals with the normally used electrical equipment on, but the engine turned off.

How to Measure the Current Drain From a Battery

This time use the multimeter as a DC ammeter. Set it to the highest current range. Connect the meter in series with a circuit consisting of one or two 1.5-V flashlight batteries and the resistance (a 10-Ω flashlight-bulb filament) you used in the previous experiment. Be sure that the positive terminal of one battery is connected to the negative terminal of the second battery. In this way the batteries are in series. Again be sure to connect the positive terminal of the meter to the high-voltage end of the circuit (nearest the positive terminal of the battery). See Figure 13. Record your current reading.

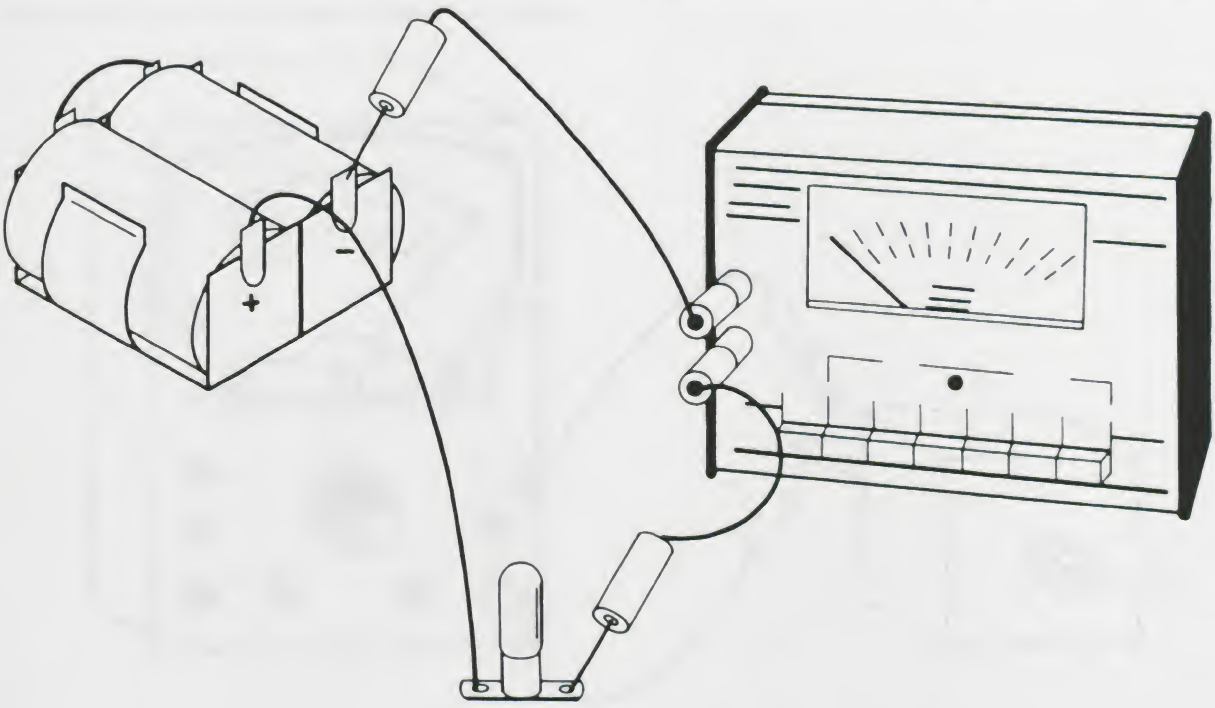


Figure 13.

What will happen to the current reading if a second identical lamp is connected in series with the first? Try it and compare the two readings.

What do you think will happen if the second lamp is connected in parallel with the first? Don't try this unless you can double the range of the meter.

Remember these basic rules for connecting ammeters and voltmeters to a circuit:

1. An *ammeter* is always connected *in series* with the circuit component whose current is to be measured.

2. A *voltmeter* is always connected *in parallel* with (across) the circuit portion under test.

3. In all DC-voltage and current measurements, the *positive* terminals of the voltmeter and/or ammeter must be connected to the *high-voltage* end, the *negative* terminals to the *low-voltage* end of the circuit.

The resistance of a good ammeter is always low enough that inserting it in the circuit does not alter the circuit current significantly. In DC-circuits, the quantity tested with a voltmeter is usually a voltage drop across a resistance (R). A good voltmeter has a much higher resistance than R, so that most of the current is forced to flow through R and not through the voltmeter. If the voltmeter resistance is not high enough, you get a false reading because of the current drawn by the meter. We say the meter *loads* the circuit. Loading effects will be studied in a later experiment. You will be able to observe measurable changes in meter readings because of meter loading. (The circuit in Step 2 of Experiment A-1 is an example.)

How to Measure Resistance

Switch to the resistance measuring function to use the multimeter as an ohmmeter. Calibrate the instrument by touching the probes together and turning the *zero-ohms-adjust* control until the pointer reads zero on the scale marked "ohms." The reason for this procedure will become clear when we discuss the basic ohmmeter circuit. The instrument is now ready for use.

Note that the zero point on the ohms scale is on the right-hand side of the scale plate and the scale divisions are crowded together toward the left-hand side, with the

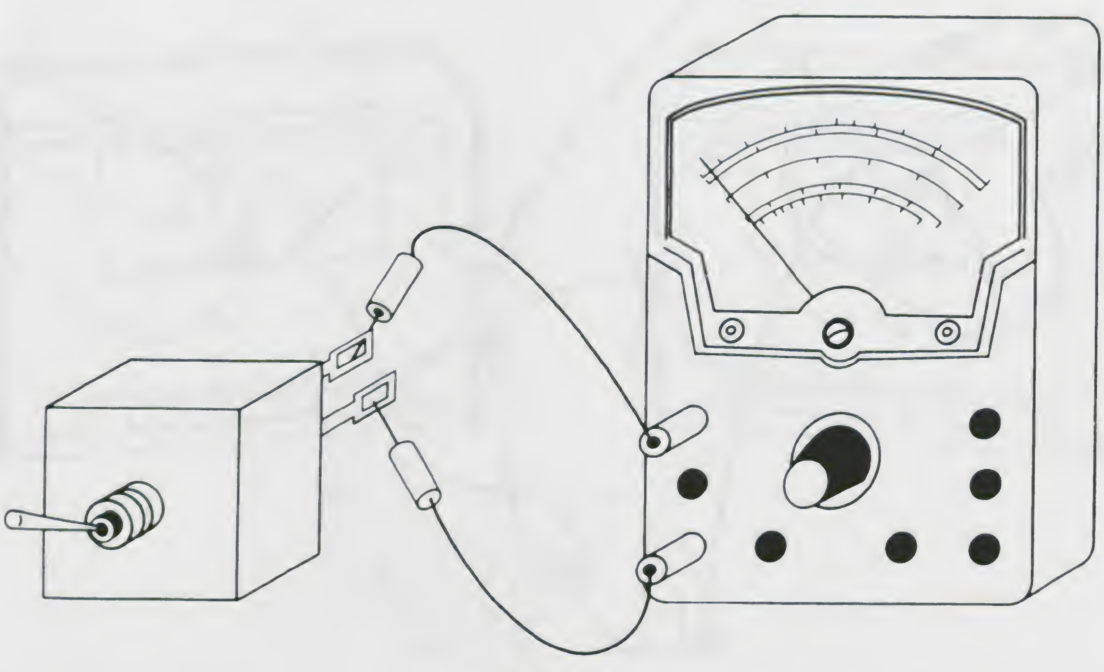


Figure 14.

end point marked "∞" (infinite resistance). Unfortunately, the farther to the left you go on the ohms scale, the more difficult it is to read the scale, and the greater is the reading error. While the ohmmeter is a convenient device for measuring resistance, it is not the most accurate.

Begin by measuring the resistances of some carbon resistors. Obtain several carbon resistors of known resistance (of the order of 100 Ω, 1 kΩ, 10 kΩ, 100 kΩ, and 1 MΩ) from your instructor. Resistance values are either printed on the resistor or given in terms of color bands which you can identify by consulting the color code in the Appendix. Select the lowest resistance, connect the probe tips to its ends, and read its resistance. Repeat, using successively larger resistors. How well do your readings agree with the given values? Which part of the ohms scale do you feel gives you the most reliable readings?

Remove the carbon resistors and connect the ohmmeter across a two-terminal toggle switch or knife switch to obtain a zero-ohms reading. Does zero ohms mean the switch is closed (on) or open (off)? Throw the switch. What resistance do you measure this time?

When the switch is in the closed position, a continuous path with essentially no resistance is formed inside the switch and the ohmmeter reads zero ohms. When the switch is in the open position no current can flow, and the resistance is infinite.

SUMMARY

A *multimeter* is a device which can be used to measure voltage, current, and resistance. The core of a multimeter is the *meter movement*, which consists of a coil between the poles of a magnet. A current through the coil causes a deflection which is indicated by a pointer attached to the coil. So the meter is basically an ammeter.

Placing a resistor in series with the meter movement enables it to be used as a *voltmeter*. The resistor placed in series is called a *multiplier*. The greater the series resistance, the higher the range of the voltmeter.

Placing a resistor in parallel with the meter movement enables it to be used as an *ammeter*. The resistor placed in parallel is called a *shunt resistor*. The smaller the resistance of the shunt, the greater the range of the ammeter.

An ammeter is connected in *series* with the circuit component whose current is to be measured. A voltmeter is always connected *in parallel* with (across) the circuit portion under test. A good ammeter has low resistance. A good voltmeter has high resistance.

PROBLEMS

1. In the circuits shown in Figure 15, all meters are identical, all resistors are 10 kΩ, and all batteries are 6 V. For each of the numbered circuits, one of the lettered circuits will have the same meter reading. Match them.

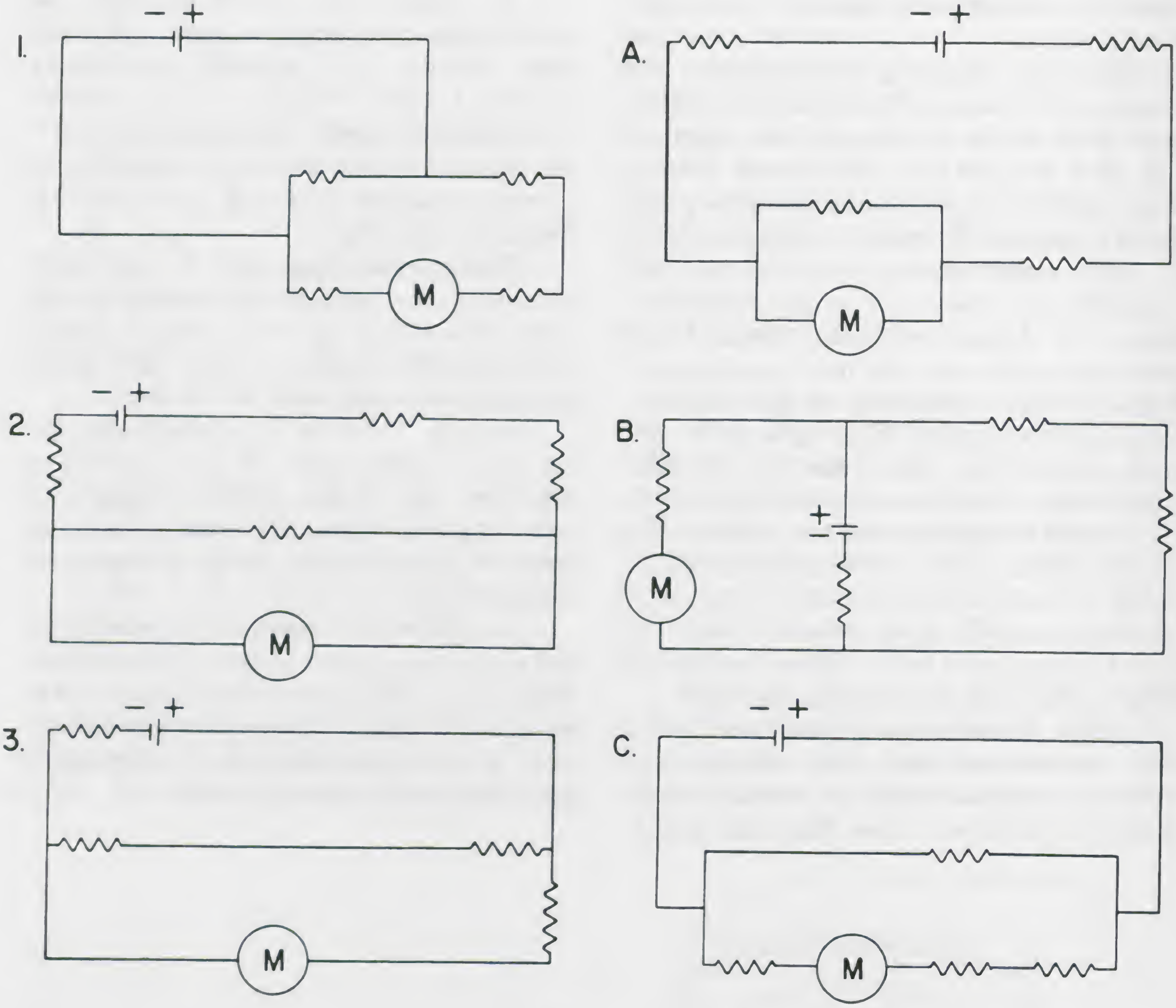


Figure 15.

2. The device shown in Figure 16 can be used as a three-range voltmeter. The terminal on the left side of the box is always used, and one of the three on the right side is used for any given measurement. Decide which should be used for low-range, medium-range, and high-range measurement.

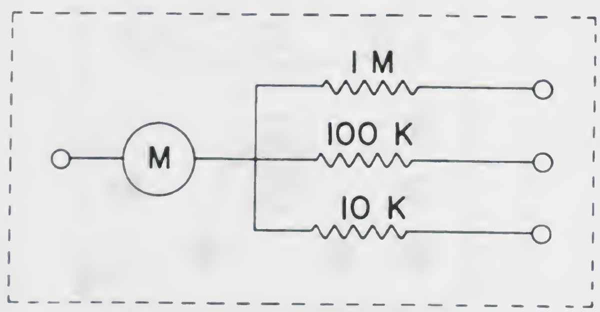


Figure 16.

3. a. Assuming suitable ranges for the circuit being investigated, which is better, an ammeter with a resistance of 1 Ω or an ammeter with a resistance of 10 Ω?

   b. In general, which is better, a voltmeter with a resistance of 1 kΩ or a voltmeter with a resistance of 10 kΩ?

4. A technician wishes to measure the current in the circuit shown in Figure 17A. He has an ammeter with a range of 1 A, but he suspects that the current in the circuit is 10 A. To protect the ammeter he puts a resistor in series with it and wires the device into the circuit as shown in Figure 17B.

   a. Can this approach protect the meter?

   b. Does the ammeter display the proper current in the circuit?

   c. Is anything wrong with this approach?

5. A technician wishes to measure the voltage drop across the resistor shown in Figure 18A. He expects the voltage drop to be about 10 V, but his voltmeter, shown in Figure 18B, has a range of 1 V. To protect the voltmeter, he adds a resistor in parallel with the meter movement and connects the device as shown in Figure 18C.

   a. Can this approach protect the meter?

   b. Does the meter give the correct value for the voltage across the resistor *R*?

   c. Is anything wrong with this approach?

Figure 17A.

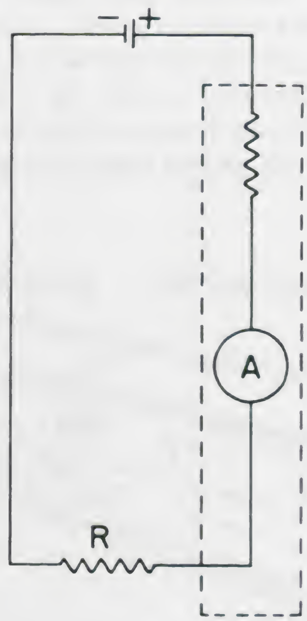


Figure 17B.

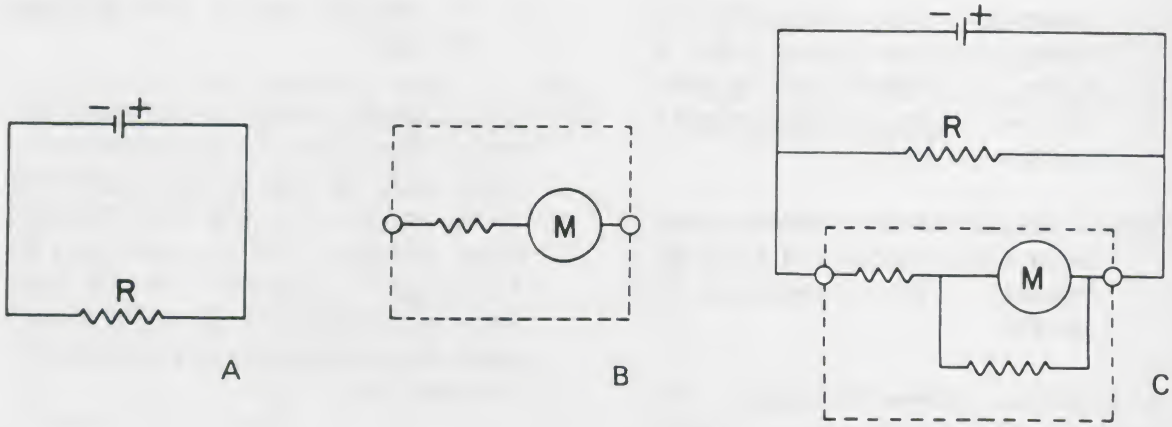


Figure 18.

SECTION B

EXPERIMENT B-1. The Voltage Divider

In this experiment, you will observe how the voltage drop along a conducting wire is related to its length. You will also learn what a *voltage divider* is and how it is used.

Procedure

1. Construct, or *wire*, the circuit shown in Figure 19. Points A and B are connected by a piece of *nichrome* wire one meter long. (Nichrome is an alloy of nickel and chromium metals.) Point C is a sliding electrical contact. Select the appropriate plug-in units from your multimeter kit to make the voltmeter and ammeter with the ranges indicated in Figure 20. Adjust the power supply so that the ammeter reads 100 mA (1 mA = 10^{-3} A). The arrow through the power-supply symbol shown in the schematic wiring diagram Figure 19B indicates that the power supply is variable.

2. Slide the electrical contact labelled point *c* from *a* to *b*. Does the ammeter reading vary? Record the current value(s) for use in the next experiment. Does the voltmeter reading vary? If so, does it vary in a regular way or does it jump around? Make a table recording the voltage corresponding to wire length, *ac*, as the wire length changes by steps of 10 cm.

3. Use the data to plot a graph of voltage (in volts) along the vertical axis against length *ac* of nichrome wire (in centimeters) along the horizontal axis. Do your experimental points suggest a straight line? If so, draw the best straight line you can through the points. (It should pass through as many points as possible and have about as many points above the line as below.)

4. You have been measuring the voltage drop V_{ac} between points *a* and *c* on the wire. For several of the same positions of point *c* as before, measure the voltage V_{cb} between points *b* and *c* of the wire. Be careful about getting the positive and

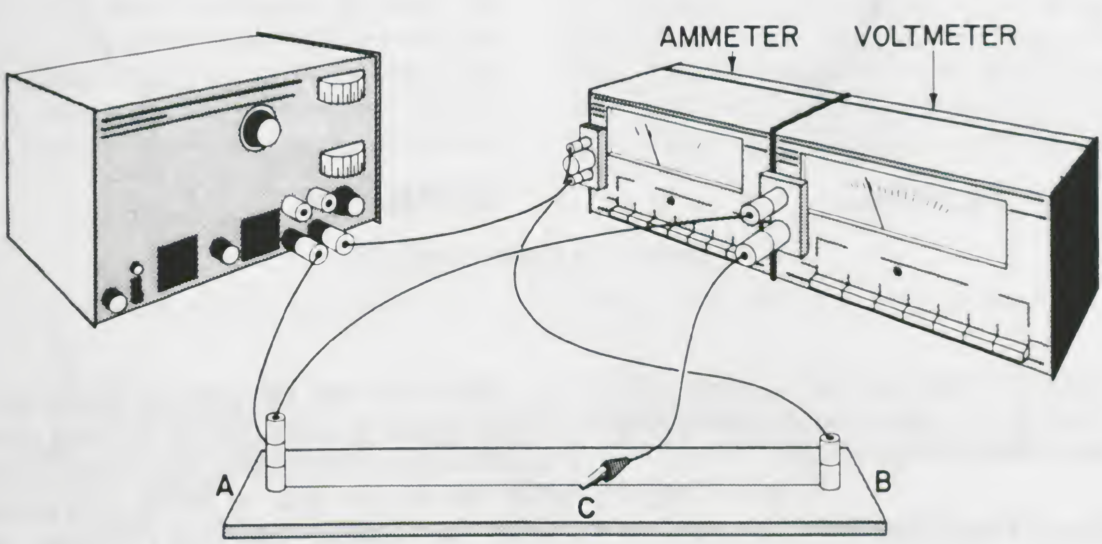


Figure 19A.

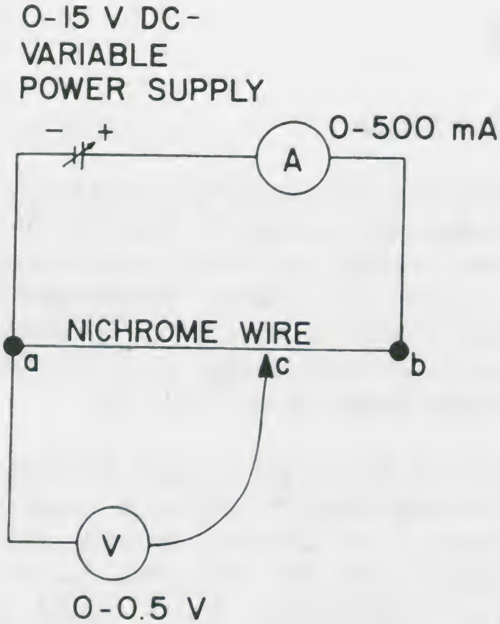


Figure 19B.

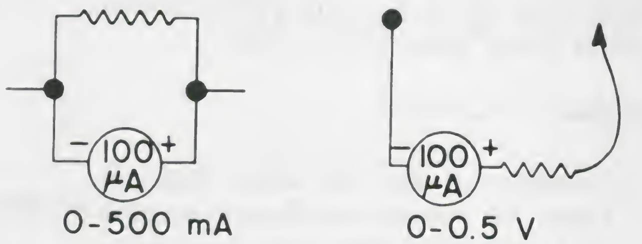


Figure 20. The ammeter and voltmeter plug-in units.

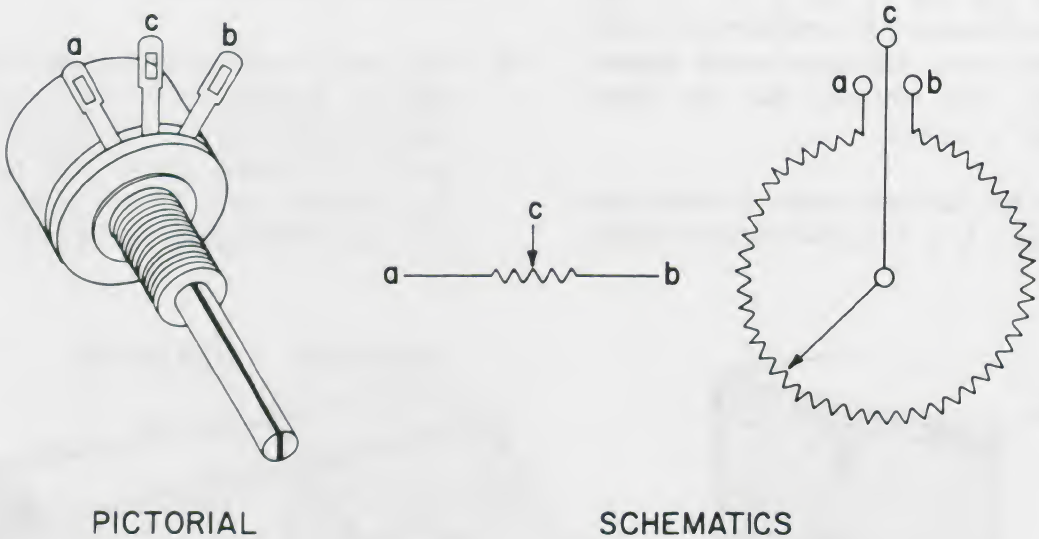


Figure 21. A potentiometer.

negative terminals of the voltmeter connected to the right places. In each case what is the sum $V_{ac} + V_{cb}$?

Discussion of Experiment B-1

What can you conclude about the relationship between voltage drop and length of wire?

The fact that the graph of voltage drop versus length is a straight line means a *linear relationship* exists between the length of wire and the voltage drop *ac* across it. Further, since the straight line passes through the origin, the voltage drop across the wire is *proportional* to the length of the wire. If the voltage drop is proportional to the length, the following is true: Reduce the length *ac* of

wire to one-half of its original length and you reduce the voltage drop across the length of wire to one-half of its original value. Reduce the length to one-third and you reduce the voltage drop to one-third, etc. Any portion of the total voltage from zero up to the maximum V_{ab} can be obtained by sliding the contact c to the appropriate position between points a and b.

Since the voltage V_{ab} is divided into the portions V_{ac} and V_{bc}, the nichrome slide wire acts as a *voltage divider*. In some applications the contact point c is continuously variable, as it was in the experiment you just completed. This provides a continuously variable voltage. A device which consists of a resistive element and a sliding contact is called a *potentiometer*, or simply a *pot*. A common form of pot is the circular arrangement shown in Figure 21 in which the slider arm is rotated like the hand of a clock.

You observed voltage drops along the nichrome wire. Are similar voltage drops found along the wires used to connect the circuit?

In theory, yes. The voltage drop along a wire is always proportional to the length of the wire. However, the voltage drop in a wire is small for large diameter wires, and is smaller for good conductors than for poor conductors. In well-designed circuits the connecting wires are made sufficiently large in diameter and of a sufficiently good conducting material that they offer very little resistance to the current. If in addition the connecting wires are made as short as possible, the voltage across them is not significant. The voltage drop in connecting wires is an important design factor. For example, if an extension cord is too long or too small in diameter, the voltage drop in the wires available at the end of the cord will not be enough to properly operate the electrical device (such as a power saw).

Example 2. Suppose you design a circuit which requires 9 V to operate. The only battery available to you, however, delivers 45 V. Draw a circuit diagram showing how the 45-V battery can be hooked up to deliver the required 9 V. Indicate on the diagram the voltage supplied by the battery and the voltage drops.

Solution. The ratio of the total voltage (45 V) to the total length of wire ab is the same as the ratio of the required voltage (9 V) to the length ac. See Figure 22.

$$\frac{45\text{ V}}{ab} = \frac{9}{ac}$$

$$ac = \frac{9}{45}\,ab = \frac{1}{5}\,ab$$

The Voltage Divider

Voltage dividers are used extensively in electrical instruments and electrical circuits. For example, a range switch in a multimeter may be part of a voltage divider with fixed taps. Such an arrangement may be preferable to having a separate resistor for each range. The voltage to be measured is applied across

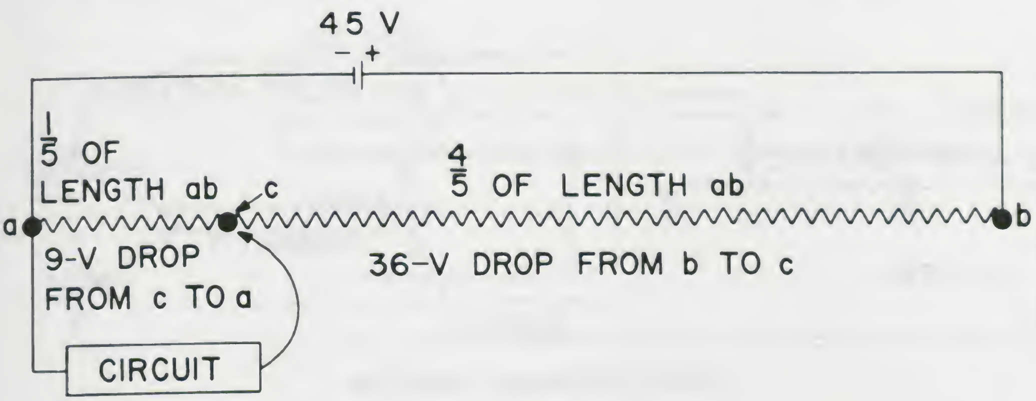


Figure 22.

the ends of the divider while the meter is connected to one of the taps and measures a known fraction of the voltage. The scale reading then includes the appropriate multiplication factor to determine the unknown voltage. The following example illustrates this point:

Example 3. An unknown voltage is applied across the ends (*a* and *b*) of the divider as in Figure 23. With the range switch in the position shown, the meter reads 3 V. This voltage is measured across one-tenth of the total resistance (50 kΩ). So the voltage across *ab* is ten times as large, or 30 V.

What voltage across *ab* would produce the same meter deflection if the range switch were moved to tap 1? To tap 2?

Solution. When the range switch is on tap 1, the full voltage V_{ab} is measured, so it must be 3 V.

When the range switch is on tap 2, the 3 V measured is across 15 kΩ, or 15/50 of the full resistance of 50 kΩ. Thus the full voltage is 3 V X (50/15), or 10 V.

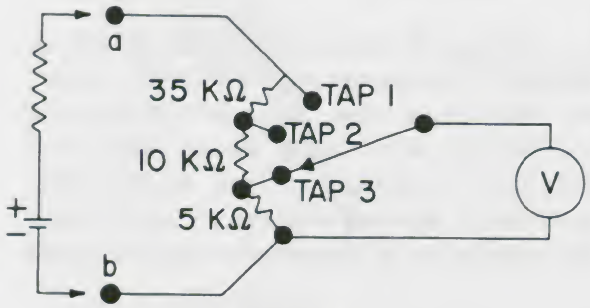


Figure 23.

The zero-adjust controls found on measuring instruments, for example, the zero-ohm set control on the multimeter, are variable voltage dividers, or potentiometers. A simplified version of the ohmmeter circuit you used for making resistance measurements is shown in Figure 24. Here the pot is connected in a different way. It does not divide the voltage of the battery, but motion of the sliding arm changes the resistance which is in series with the battery. This in turn varies the current in the circuit. When used in this manner, the pot is called a *rheostat*. To calibrate the ohmmeter, connect the probe tips to short-circuit the input terminals. Then adjust the zero-ohm control until the pointer indicates full-scale deflection. Full-scale deflection is marked "zero ohms" on the scale plate. When you separate the probe tips, the short-circuit is replaced by an open-circuit, and the meter returns to its zero-current position. This point on the scale is marked "infinite ohms (∞)" because an open circuit across the input terminals is the same as having infinite resistance between them. These two extreme points then define a scale that is calibrated in ohms. Any resistance *R* connected between the input terminals causes the pointer to deflect to a point somewhere between these two extremes. Half-scale deflection occurs when *R* equals the resistance of the meter movement plus the resistance of the rheostat. Why?

The ohms scale reads from right to left because greater resistance placed between the input terminals results in less current and thus less pointer deflection.

The zero-ohm adjustment should be performed before each test because it is different

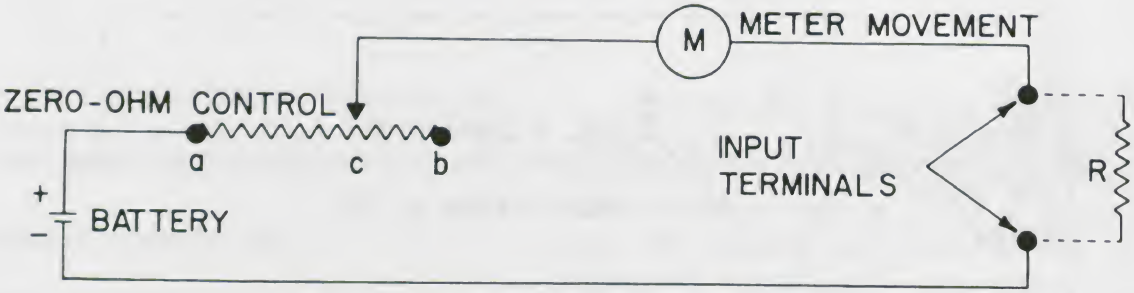


Figure 24. Ohmmeter (simplified).

for different resistance ranges and it also varies with age of the battery. When full-scale deflection can no longer be obtained, the battery should be replaced.

Another application of the potentiometer is that of measuring an unknown voltage. A known voltage source is connected to an unknown source so they are "bucking" each other. See Figure 25. The unknown voltage is determined by moving the slider arm until the meter deflection is zero. No current flows when the unknown voltage just "balances" the voltage drop across *ac*. The more sensitive the meter, the more accurate is this *null* measurement. The unknown voltage is then determined from the length *ac*. The same principle is used in a potentiometric recorder, a device for translating electrical signals into the movement of a pen over a chart.

A *linear-motion rheostat* is a control device which detects unwanted drift motion in mechanical systems. By means of the rheostat a voltage signal is sent to a control circuit which corrects the motion and restores the mechanical component to its equilibrium position.

In Figure 26, the slider is shown mounted on an arm. If the arm moves, so does the slider. The change in the voltage drop in the rheostat produces a voltage signal. In the design shown the slider shorts out a portion of the resistance, a common way of operating a potentiometer as a rheostat.

The principle of a liquid-level sensor utilizing a *float-operated rheostat* is shown in Figure 27. A change in level of liquid causes the slider to move along the resistance. The resulting change in voltage is transmitted to a meter or control circuit. This is how fuel gauges in many cars operate.

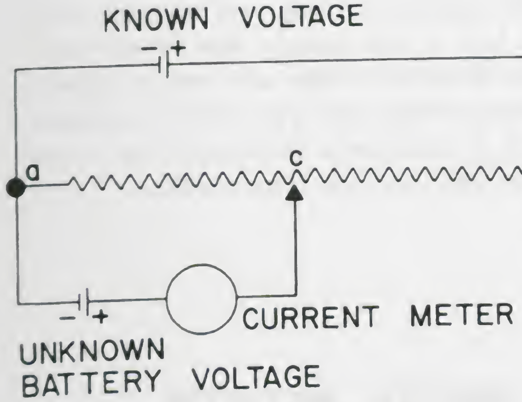


Figure 25. Potentiometer.

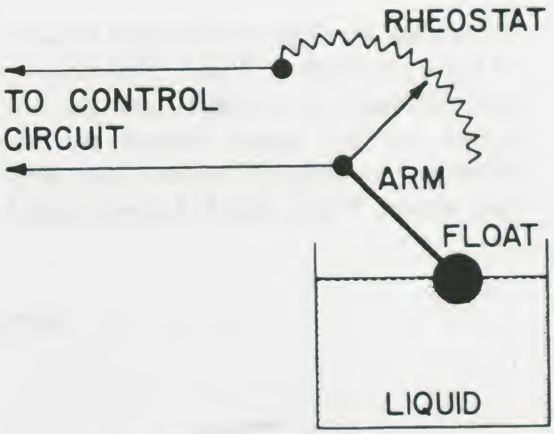


Figure 27. Float-operated rheostat.

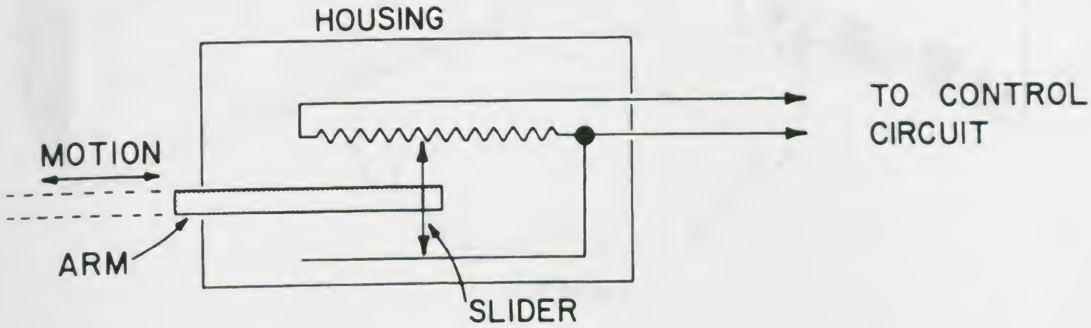


Figure 26. Linear-motion rheostat.

EXPERIMENT B-2. Ohm's Law

In this experiment, you will observe how voltage and current vary for a given resistor. The interrelation between voltage, current, and resistance is called *Ohm's Law*. You will see how to use Ohm's Law to compute resistance.

Procedure

1. Wire the circuit shown in Figure 28.

2. Turn on the power supply and take several current and voltage readings between zero and the maximum voltage obtainable from the supply.

3. On graph paper plot voltage (in volts) along the vertical axis against the current (in amperes) along the horizontal axis. Do you get a straight-line graph?

4. Determine the slope of the graph in units of volts per ampere (V/A). (The *slope* is the difference in voltages between two points on the graph divided by the difference in currents between the same two points. This is called the *rise* divided by the *run* of the line.) For convenience, one volt/ampere is called one ohm (Ω). An ohm is the basic unit of resistance. The slope of your graph represents the resistance R. Compare the value of the slope with the resistance of the resistor as given by the color bands. (Check the color code of resistors in the Appendix.)

If you know the equation of a straight line, you can write down the equation relating voltage V, current I, and resistance R. This equation is

$$V = IR \tag{1}$$

It is called Ohm's Law. Study Figure 28 carefully so that you can readily identify the quantities V, I, and R. V is the voltage drop across the resistor R. I is the current through R (in amperes). R is measured in ohms.

The significant thing to remember about Ohm's Law is the straight line (linear) relationship between voltage and current. Ohm's Law is used every time you analyze a circuit. Since it is extremely important for future work, be sure you remember it well.

PICTORIAL

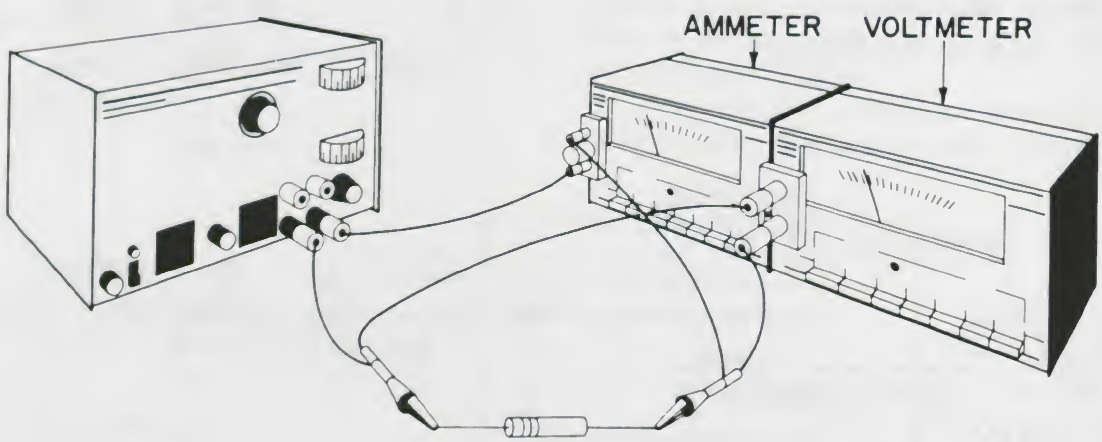


Figure 28A.

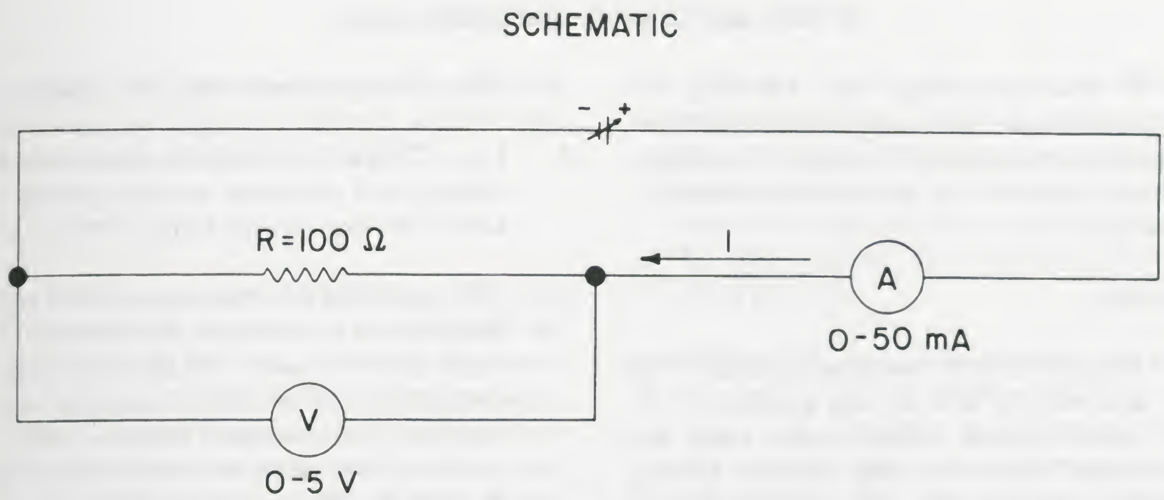


Figure 28B.

EXPERIMENT B-3. Resistances in Series

In this experiment, you will find the single resistance which replaces a combination of resistances connected in series. This single resistance is called the *effective* or *equivalent* resistance.

Procedure

1. Wire the circuit shown in Figure 29. The resistors R_1 and R_2 are connected "in series" which means "one after the other," with the same current flowing through each. (Suggested values: $R_1 = 500\ \Omega$, $R_2 = 1000\ \Omega$.) Hook up the voltmeter to points *a* and *c*. Switch on the power supply and use the pot to increase the voltage until the deflection on one of the meters reaches its maximum value. Keep the voltage supply fixed at this value.

2. Measure and record the voltages across *ac*, *ab*, and *bc*. What relationship do you see among these voltages?

3. Measure the voltages across *cd* and *ad*. How do they compare with those measured in Step 2?

4. What is the current in each resistor? Use the ammeter to measure it if you have doubts. For example, you might place the ammeter between the two resistors.

5. Does Ohm's Law hold for the current, voltage, and resistance between points *a* and *b*? Between points *b* and *c*?

6. Use the results of your observations and Ohm's Law to calculate the value of a single resistor which will give the same current and voltage readings as the two resistors now connected between points *a* and *c*. Check your answer by replacing R_1 and R_2 with a single resistance of this value and measuring the voltage and current. What is the relationship between the value of this single resistance R and the combination of R_1 and R_2? Express the relation as an equation.

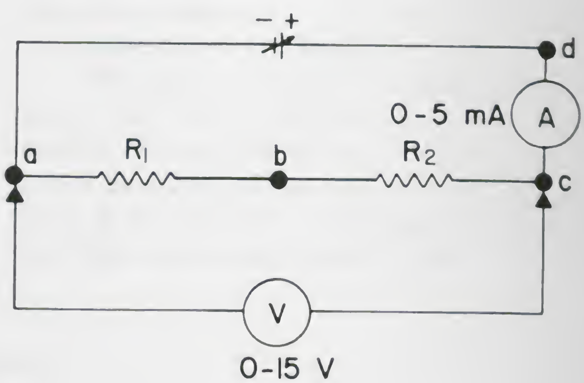


Figure 29.

EXPERIMENT B-4. Resistances in Parallel

Here you will find the single effective resistance necessary to replace a combination of resistances connected in parallel.

Procedure

1. Wire the circuit shown in Figure 30. The resistors R_1 and R_2 are said to be connected "in parallel" which means "one next to the other," each carrying part of the current. The circuit is thus divided into *branches*, one branch which contains the resistor R_1, the other the resistor R_2. (Suggested values: R_1 = 500 Ω, R_2 = 1000 Ω.) Hook up the voltmeter to points *a* and *b*. Turn up the power supply until one of the meters reads full-scale. Keep the power supply setting fixed to this value.

2. Measure and record the voltage across *ab* and the current in *bc*.

3. Shift the ammeter into the branch containing R_1 and measure the current (I_1) flowing through R_1. Similarly, measure the current (I_2) flowing through the branch containing R_2. Do you see a relationship between the branch currents and the current in *bc*?

4. Are your voltage and current measurements for the branch containing R_1 in agreement with Ohm's Law? How about the branch containing R_2?

5. Calculate the single resistance R which will replace the parallel combination of R_1 and R_2, such that the same voltage is maintained across points *a* and *b*, and the same total circuit current is indicated by the ammeter. Use Ohm's Law in the form $R = V/I$.

6. Verify your answer by replacing R_1 and R_2 with a single resistance having the value you calculated and observing that the current and voltage values remain unchanged. Can you find an equation relating R, R_1, and R_2? (If you have difficulty, read the next section on "Applications of Ohm's Law.")

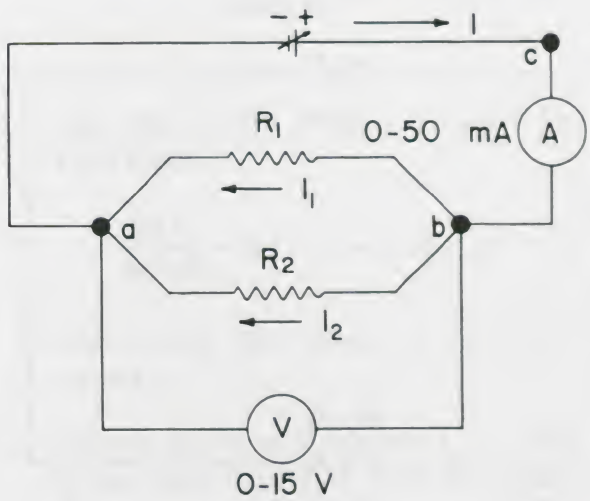


Figure 30.

APPLICATIONS OF OHM'S LAW

The relationship between the current in a resistor and the voltage drop across it is the main topic studied in Experiment B-2. The results are expressed in *Ohm's Law: the voltage drop across a circuit element is proportional to the current in the element,* where the constant of proportionality is the resistance. In equation form, we write

$$V = IR$$

A circuit element which has a constant resistance is said to obey Ohm's Law. In applying Ohm's Law, the usual units are V in volts (V), I in amperes (A), and R in ohms (Ω).

Example 4. Determine the current in the circuit shown in Figure 31.

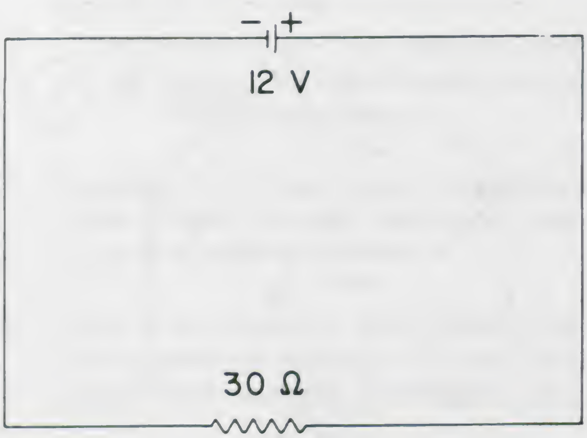


Figure 31.

Solution. Since

$$V = IR$$

$$I = \frac{V}{R} = \frac{12\text{ V}}{30\ \Omega} = 0.4\text{ A}$$

Some complications are introduced in the circuit in Figure 32. How does one determine the voltage drop across the 100-Ω resistor or the current in the 50-Ω resistor? The analysis can be simplified by using the results of Experiments B-3 and B-4.

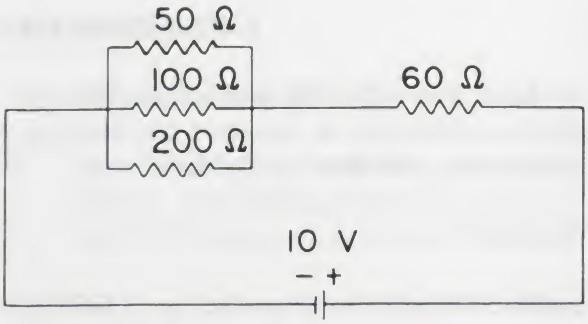


Figure 32.

Two resistances R_1 and R_2 connected in *series* have the same effect on a circuit as a single resistance R given by

$$R = R_1 + R_2 \tag{2}$$

Two resistances R_1 and R_2 connected in *parallel* have the same effect on the circuit as a single resistance R given by

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} \tag{3}$$

These rules can be extended to include any number of resistances in series or parallel.

The problem of analyzing the circuit shown in Figure 32 is treated in Examples 5 and 6.

Example 5. A circuit contains three resistors connected in parallel. Their resistances are 50 Ω, 100 Ω, and 200 Ω. Find the equivalent resistance of the three resistors.

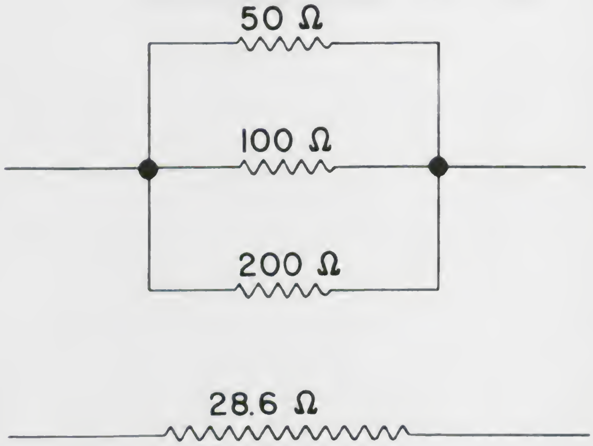


Figure 33.

Solution.

$$\frac{1}{R}=\frac{1}{50\ \Omega}+\frac{1}{100\ \Omega}+\frac{1}{200\ \Omega}$$

$$=\frac{4}{200\ \Omega}+\frac{2}{200\ \Omega}+\frac{1}{200\ \Omega}$$

$$=\frac{7}{200\ \Omega}$$

Thus

$$R=\frac{200\ \Omega}{7}=28.6\ \Omega$$

Equivalent resistance is a useful concept because it simplifies a circuit so Ohm's Law can be applied. This point is illustrated by Example 6 in which we analyze the circuit shown in Figure 32. For convenience, the same circuit is shown again in Figure 34.

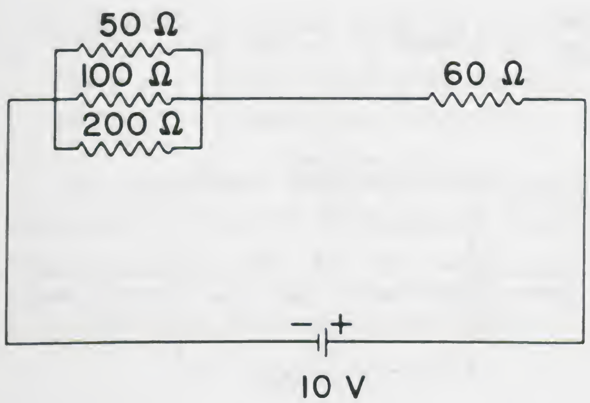


Figure 34.

Example 6. A circuit contains three resistors in parallel (50 Ω, 100 Ω, and 200 Ω, respectively). The parallel combination is connected in series with a single 60-Ω resistor. If the battery provides 10 V, find the current in each resistor.

Solution.

1. Draw the circuit diagram (Figure 34).

2. Replace the parallel combination by its equivalent resistance. From the previous example, the equivalent parallel resistance is 28.6 Ω.

3. Further reduce the series combination of 28.6 Ω and 60 Ω to its equivalent resistance. The equivalent series resistance is 28.6 Ω + 60 Ω = 88.6 Ω. The circuit is now reduced to the simple form which enables you to apply Ohm's Law. (See Figure 35.)

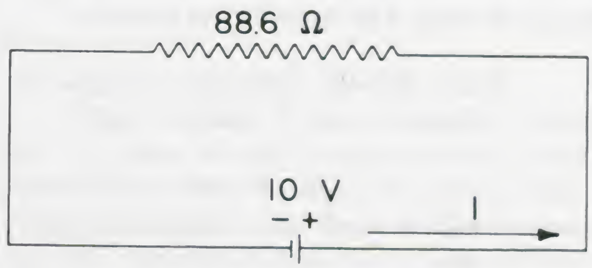


Figure 35.

4. The total current I in the circuit is, by Ohm's Law,

$$I=\frac{10\ \mathrm{V}}{88.6\ \Omega}=0.113\ \mathrm{A}=113\ \mathrm{mA}$$

This is also the current in the 60-Ω resistor.

5. To find the branch currents I_1, I_2, and I_3, we must determine the voltage drop V across the parallel resistances. The voltage drop across the equivalent parallel resistance is $V_P = 0.113\ \mathrm{A} \times 28.6\ \Omega = 3.23\ \mathrm{V}$. Since this is the voltage drop across *each* of the parallel resistors (again, by Ohm's Law),

$$I_1=\frac{3.23\ \mathrm{V}}{50\ \Omega}=0.0646\ \mathrm{A}=64.6\ \mathrm{mA}$$

$$I_2=\frac{3.23\ \mathrm{V}}{100\ \Omega}=0.0323\ \mathrm{A}=32.3\ \mathrm{mA}$$

$$I_3=\frac{3.23\ \mathrm{V}}{200\ \Omega}=0.0162\ \mathrm{A}=16.2\ \mathrm{mA}$$

A convenient way of checking your computation is to add up the branch currents. Their sum must equal the total current I (113 mA). Why?

The equations for the effective resistances of resistors connected in series and in parallel were discovered experimentally in Experiments B-3 and B-4. These equations can also be derived using Ohm's Law.

The total voltage drop across a combination of resistors in series is the sum of the individual drops. For two resistors in series,

$$V = V_1 + V_2$$

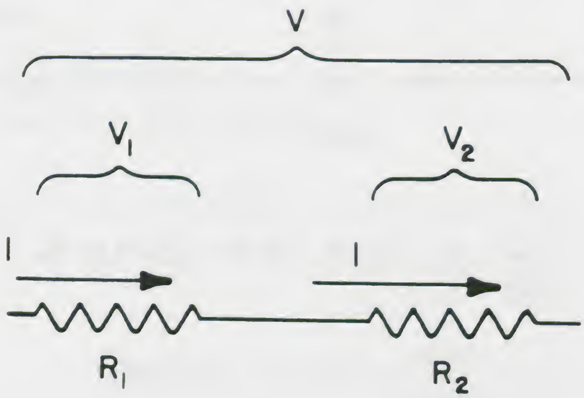


Figure 36.

Each resistor carries the same current I because all charge which flows through R_1, must also flow through R_2. Charge does not "pile up," so the rate at which charge flows through R_1 is the same as the rate at which charge flows through R_2.

By Ohm's Law,

$$V = IR$$

where R is the equivalent resistance we wish to find. Furthermore,

$$V_1 = IR_1$$

and

$$V_2 = IR_2$$

Combining these three equations leads to

$$IR = IR_1 + IR_2$$

Dividing each term by I, we get the result

$$R = R_1 + R_2 \qquad (2)$$

for the effective resistance of two resistors connected in series. This process can be extended to any number of resistors in series.

When two resistors are connected in parallel, the voltage drop V is the same for each resistor. The total current (I) in the circuit is the sum of the branch currents I_1 and I_2. Why? Applying Ohm's Law,

$$I_1 = \frac{V}{R_1} \text{ and } I_2 = \frac{V}{R_2}$$

We also have

$$V = (I_1 + I_2)R$$

where R is the single equivalent resistance we seek.

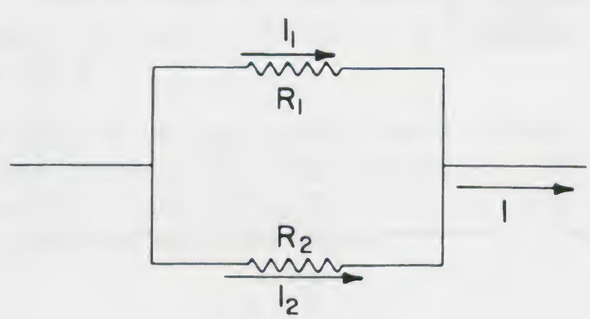


Figure 37.

Substituting into this equation the expressions for I_1 and I_2,

$$V = \left(\frac{V}{R_1} + \frac{V}{R_2}\right)R$$

Dividing through by V, we get

$$1 = \left(\frac{1}{R_1} + \frac{1}{R_2}\right) R$$

or,

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

which is the desired relation. This procedure can be extended to any number of resistors in parallel.

KIRCHHOFF'S LAWS (OPTIONAL)

When a circuit contains more than one voltage source, added complications are introduced. They may be resolved by using *Kirchhoff's Laws.* These laws are two common-sense statements which come from the physical principles of conservation of charge and conservation of energy. They can be stated as follows:

1. When several branches of a circuit meet in a junction, the total current entering the junction equals the total current leaving.

2. The algebraic sum of the *EMF*'s* in any loop of a circuit is equal to the algebraic sum of the voltage drops in that loop.

To understand what these statements mean, look at the rather complicated circuit of Figure 38A. Without Kirchhoff's Laws it would be impossible to find the currents and voltage drops in the various parts of the circuit. However, Kirchhoff's Laws allow one to isolate the various parts of the circuit and to write equations for them. For example, in Figure 38B, we can look at the junctions labelled *a* and *b,* and write current equations for each of them. Currents I_1 and I_3 are entering junction *a* and I_2 is leaving. Thus, from Kirchhoff's first law,

$$I_1 + I_3 = I_2$$

At junction *b,* the same equation results.

What happens if you unluckily picked one or more of the currents in the wrong direction? It doesn't matter; if you do everything consistently, the signs of the answers tell you the actual direction of any current. For example, if one answer had turned out to be $I_1 = +2$ A, then I_1 actually does flow in the direction you chose. On the other hand, if $I_1 = -2$ A is the answer, then I_1 is flowing in the opposite direction from your arbitrary choice.

Now look at one loop of the circuit, such as the one indicated in Figure 38C. There are two voltage sources in this loop, V_1 and V_2, and we shall go around the loop in a clockwise direction, as indicated. Here, one needs to be very careful about the signs used. There are two rules for doing this:

*EMF is an abbreviation for *electromotive force,* which is the term often used for the voltage provided by a voltage source. EMF's are measured in volts.

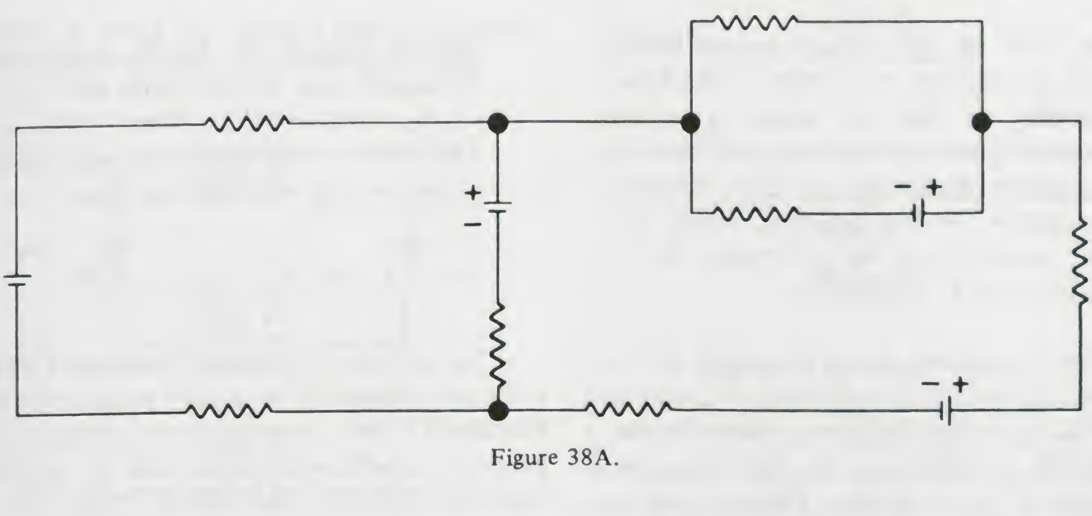


Figure 38A.

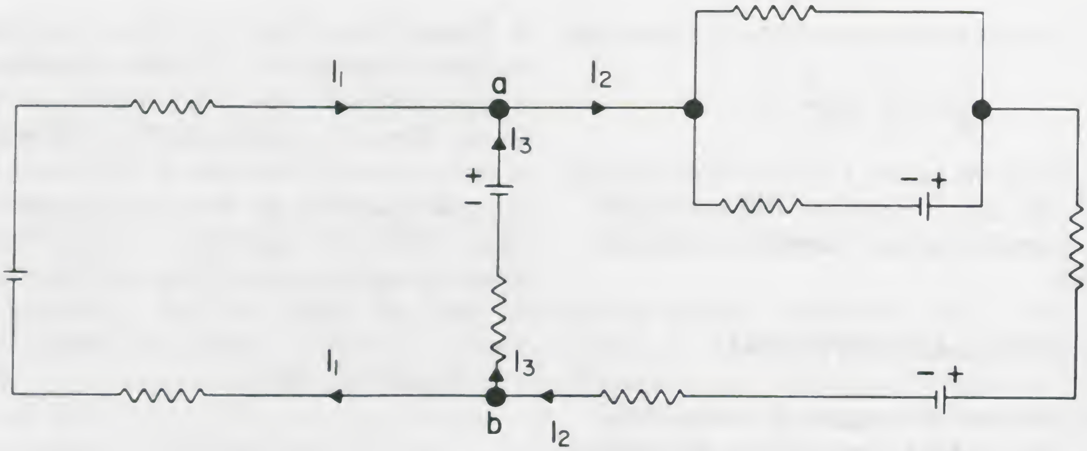


Figure 38B.

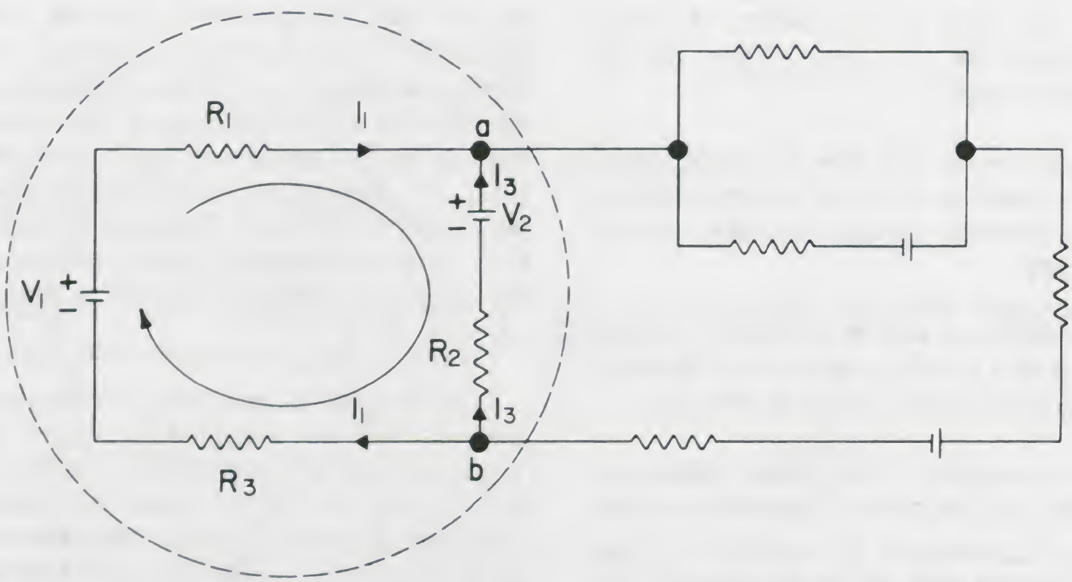


Figure 38C.

1. The EMF of any voltage source which tends to produce a current in the same direction as that in which you are proceeding around the loop is chosen to be positive. Otherwise the EMF is taken as negative. In this example, where the loop is chosen to be clockwise, V_1 is positive and V_2 is negative.

2. When proceeding across a resistor in the loop, where the direction of the loop is the same as the direction chosen for the current in that part of the loop, the voltage drop is positive. Otherwise, it is negative. In each case, the size of the voltage drop is IR. In the loop under discussion, the voltage drops are $+I_1 R_1$, $-I_3 R_2$, and $+I_1 R_3$. Thus, combining EMF's from voltage sources and voltage drops, we can write the equation:

$$V_1 - V_2 = I_1 R_1 - I_3 R_2 + I_1 R_3$$

By picking appropriate loops and directions in a circuit, it is usually possible to use Kirchhoff's laws to write down enough independent simultaneous equations so that the unknown currents and voltage drops can be computed.

Example 7. Calculate the current I in the circuit shown in Figure 39.

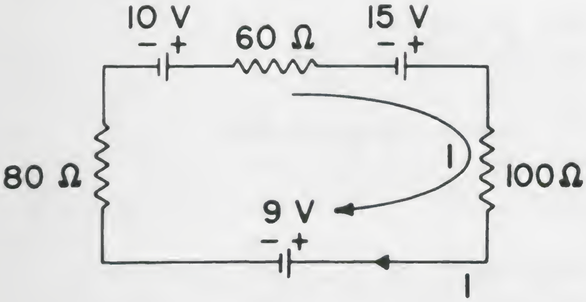


Figure 39.

Solution. In this circuit there is only one loop, thus only one current, and we choose to go around it in a clockwise direction. We also choose the current to be clockwise. The sum of the EMF's is then +10 V + 15 V − 9 V. The sum of the voltage drops is $I \times 60\ \Omega + I \times 100\ \Omega + I \times 80\ \Omega$. Thus

$$10\text{ V} + 15\text{ V} - 9\text{ V} = (60\ \Omega + 100\ \Omega + 80\ \Omega)I$$

$$16\text{ V} = (240\ \Omega)I$$

$$I = \frac{16\text{ V}}{240\ \Omega} = 0.067\text{ A}$$

$$I = 67\text{ mA}$$

You might use this result to check that the sum of the voltage drops is 16 V.

Example 8. Find the current being supplied by the battery in the circuit of Figure 40A.

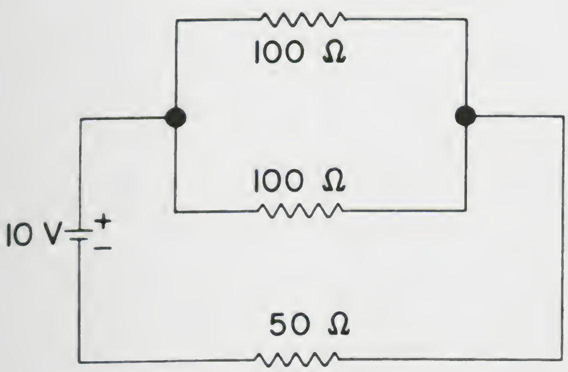


Figure 40A.

Solution. First, choose the currents at a junction, as shown in Figure 40B. Then, the current we wish to find is I_1, and $I_1 = I_2 + I_3$.

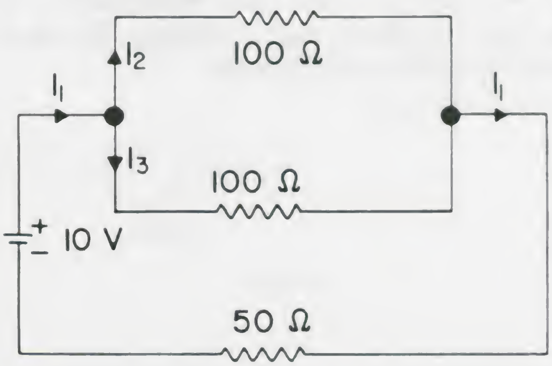


Figure 40B.

Now look at the two loops indicated in Figure 40C. We need *two* loops because, since there are three unknown currents, three simultaneous equations are needed to get the solution. The third equation is provided by the relation among the currents at a junction point.

$$I_1 = I_2 + I_3$$

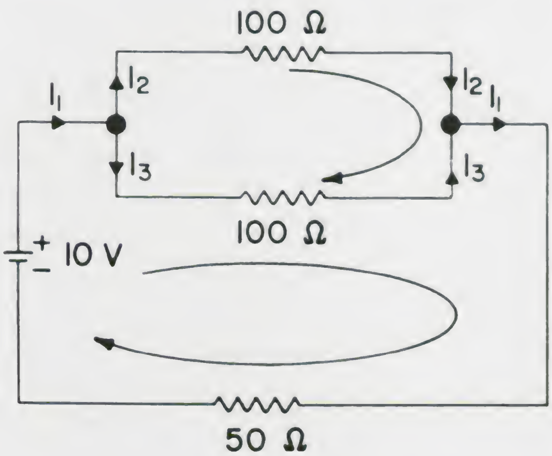


Figure 40C.

In the upper loop there are no voltage sources, so $(100\ \Omega)\, I_2 - (100\ \Omega)\, I_3 = 0$, or $I_2 = I_3$. The lower loop passes only through the middle resistor and the bottom one, as well as through the voltage source. It does not pass through the top resistor. Then, setting

the sum of the EMF's equal to the sum of the voltage drops:

$$10 \text{ V} = (100\ \Omega)\, I_3 + (50\ \Omega)\, I_1$$

We now have our three equations. Combining the first two gives $I_1 = 2\, I_3$. Putting this result into the third equation yields

$$10 \text{ V} = (100\ \Omega) \times \tfrac{1}{2} I_1 + (50\ \Omega) I_1$$

$$= (50\ \Omega) I_1 + (50\ \Omega) I_1 = (100\ \Omega) I_1$$

$$I_1 = \frac{10 \text{ V}}{100\ \Omega} = 0.1 \text{ A}$$

$$I_2 = I_3 = \tfrac{1}{2} I_1 = 0.05 \text{ A}$$

EXPERIMENT B-5. Non-Linear Behavior

This experiment will demonstrate a case where Ohm's Law is not valid.

In Experiment B-2 you observed how the voltage drop V across a resistance R varies with current I. You obtained a straight-line, or *linear*, relationship between V and I. The constant value of the slope of the graph is the resistance R. This linear relationship is Ohm's Law.

Now we ask the question: Does Ohm's Law hold for all resistors? Is it possible that the graph of voltage V plotted against current I for a given resistor is not a straight line?

Let's try an experiment in which we use as a resistance the filament of a flashlight bulb.

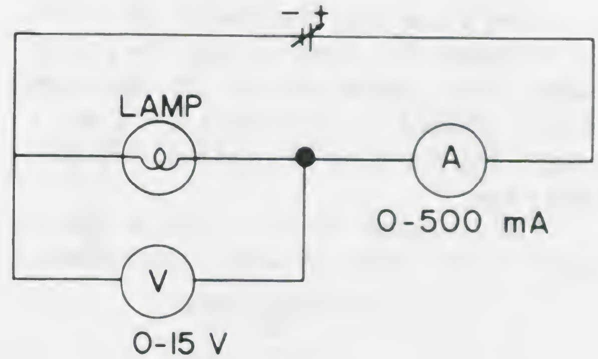


Figure 41.

Procedure

1. Wire the circuit shown in Figure 41.

2. By varying the power supply output, measure and record current and voltage for several values of the voltage between zero and the maximum obtainable.

3. Plot a graph of voltage (in volts) along the vertical axis against current (in amperes) along the horizontal axis. Does Ohm's Law hold in this case? Recall that a straight-line graph implies unchanging resistance. What do you think is happening to the resistance of the lamp filament as the current in it increases?

NON-OHMIC DEVICES

Ohm's Law does *not* describe all materials or devices. For example, since the plot of voltage drop against current for the lamp filament studied in Experiment B-5 is *not* a straight line, the lamp filament does not obey Ohm's Law.

The resistance of any device is always given by the ratio of voltage to current.

$$R = \frac{V}{I}$$

But for many electronic devices the resistance changes as the applied voltage changes.

Circuit elements which obey Ohm's Law are called *linear* or *ohmic* elements. Elements which do not obey Ohm's Law are called *non-linear* or *non-ohmic* elements. In the latter case, the current through the element is not proportional to the voltage across the resistor.

Most metals are ohmic in behavior as long as the temperature is constant. However, for most pure metals the resistance increases as temperature increases. Thus a departure from Ohm's Law is expected, particularly if the temperature changes are large as they are in lamp filaments.

The dependence of resistance on temperature has a practical application: Thermometers are constructed using resistance as a means of measuring temperature. *Resistance thermometers* using platinum wire are extremely precise over a wide range of temperatures below the melting point of platinum. Figure 42 shows how the resistance of a platinum wire varies with its temperature. While portions of the graph appear to be linear, the overall picture is not a straight line.

Some materials have resistances which vary greatly with temperature. These materials are useful as thermometers and for temperature control. A thermistor is such a device. Thermistors are made by combining metallic oxides of manganese, iron, cobalt or nickel with ceramic material. The resultant materials are shaped into beads, rods, or disks.

The resistance–temperature curve for a thermistor is shown in Figure 43. The thermistor is non-ohmic and, unlike metals, has greater resistance when it is cold than when it is warm.

Color television sets and electronic organs use devices called *photo-* or *light-dependent* resistors (LDR). Ohm's Law does not hold for these devices since their resistances vary greatly with the amount of light they receive. The resistance of an LDR may

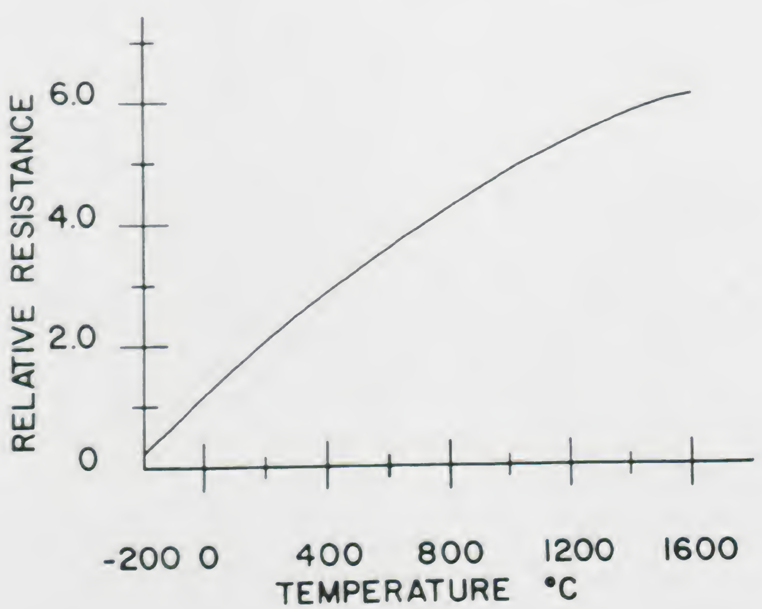


Figure 42.

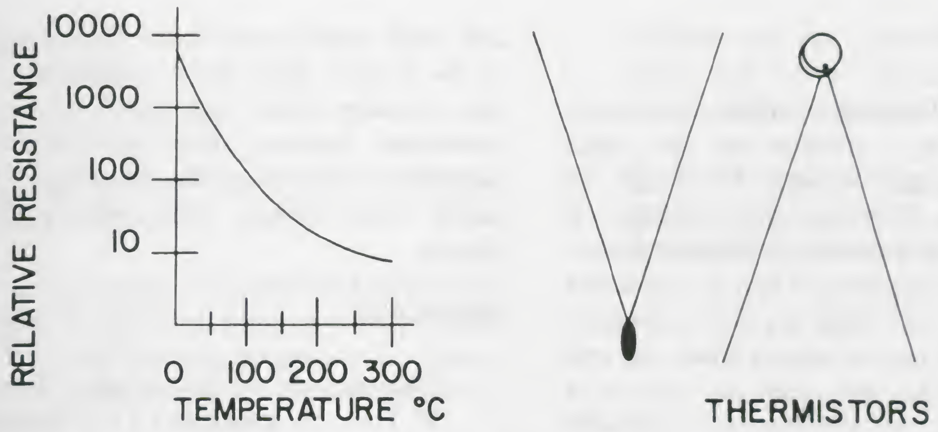


Figure 43.

be a few megohms in darkness and may drop to about 100 Ω when the resistor is exposed to light. The change in resistance is brought about by interaction of the material in the device with light energy.

Other important non-linear devices are all types of "solid-state" *diodes* and *transistors*. The current-voltage relation of a silicon crystal diode, for example, is shown in Figure 44. (In electronics it is customary to plot current along the vertical axis and voltage along the horizontal axis.) The graph, which is not a straight line, is called the diode's *characteristic curve*. Such diodes serve as *rectifiers* which offer low resistance to a current in one direction (called the "forward" direction), but high resistance to a current in the other ("reverse") direction. The current remains practically zero as the voltage across the device increases in the negative direction. Current passes through the semiconductor diode in the forward direction only unless the reverse voltage is made so large that "breakdown" occurs.

Vacuum tubes and *gas-filled tubes* also show non-ohmic behavior. A vacuum diode acts as a rectifier which has a low resistance in one direction and a high resistance in the other. Its characteristic curve resembles that of the semiconductor diode, except that there is no breakdown of resistance as the reverse voltage is increased.

Semiconductor devices, vacuum tubes, and gas-filled tubes are all non-ohmic because their resistances vary, depending on the way electric charges behave inside those devices under operating conditions.

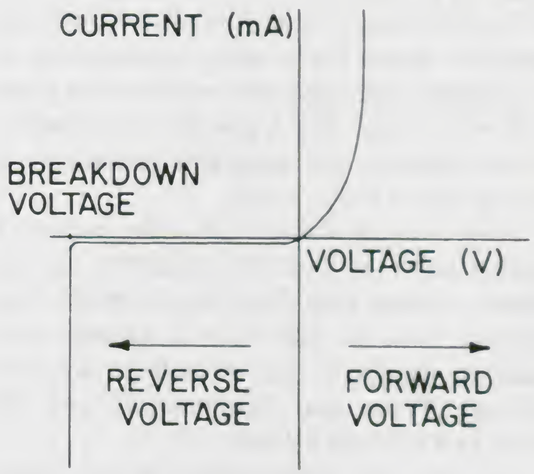


Figure 44.

SUMMARY

A *voltage divider* provides an output voltage which is a fraction of the input voltage. The output voltage will range between zero and the total input voltage. A *potentiometer* is a variable voltage divider which has three terminals. Two are connected across a resistor, the third is a sliding contact, or slider, which can be moved from one end of the resistor to the other to provide a variable voltage. A *rheostat* is a variable resistor, which has two terminals. One is fixed, the other is a sliding contact or slider. Motion of the slider changes the resistance, thereby controlling the current in the circuit.

Voltage dividers are used in multimeters as part of the circuit which provides the meter ranges; in potentiometers for measuring unknown voltages; and in potentiometric recorders for recording changes in voltage. *Rheostats* are used to control the current in a circuit. Applications include the zero-ohms control of the ohmmeter, the linear-motion rheostat, and the liquid-level sensor.

A circuit component for which the current is proportional to the voltage drop is said to obey *Ohm's Law*, $V = IR$, where R has a constant value. For a *series combination* of two resistors, the equivalent resistance is given by $R = R_1 + R_2$. For a *parallel combination* of two resistors, the equivalent resistance is given by $1/R = 1/R_1 + 1/R_2$.

The sum of currents flowing out of a junction point in a circuit equals the sum of currents flowing into that junction point. The algebraic sum of EMF's in a circuit loop equals the algebraic sum of voltage drops in a circuit. These two fundamental laws are known as *Kirchhoff's Laws.*

A *linear* or *ohmic* device is one which obeys Ohm's Law. A *non-linear* or *non-ohmic* device is one which does not. If the device is ohmic, its resistance remains fixed for given current and voltage changes. This is true for most conductors made of metal alloys over a wide range of current and voltage changes.

Certain metallic conductors and "solid-state" devices (such as thermistors) are non-ohmic because their resistances vary noticeably with temperature in the operating range of the devices. Such devices as diodes, transistors, vacuum tubes, and gas-filled tubes are non-ohmic because their resistances vary, depending on the way electric charges behave inside these devices under operating conditions.

PROBLEMS

1. Suppose you need a voltage source of 3 V. You have available a 15-V battery and resistors of 1 Ω, 2 Ω, 4 Ω, and 8 Ω. Draw the diagram for a circuit which will provide the desired voltage.

2. For the circuit shown in Figure 45, calculate the voltages between *a* and *b*, between *a* and *c*, and between *a* and *d*.

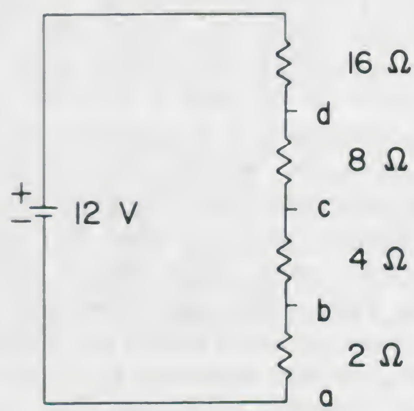


Figure 45.

3. Three resistors with values of 100 Ω, 150 Ω, and 200 Ω are connected in parallel. Calculate the equivalent resistance.

4. If you have available three resistors, 100 Ω, 200 Ω, and 400 Ω, it is possible to provide many different total resistances. For example, putting the 100-Ω and 200-Ω resistors in parallel gives 67 Ω. State how you would connect the resistors to produce each of the following resistances (the values are rounded off to the nearest Ω):

a. 700 Ω
b. 500 Ω
c. 57 Ω
d. 467 Ω

There are at least another ten combinations possible.

5. A 12-V battery is connected to two 6-Ω resistors. Calculate the circuit current (a) if the resistors are connected in series, and (b) if the resistors are connected in parallel.

6. For the circuit shown in Figure 46, calculate (a) the currents in the 10-Ω, 20-Ω, and 60-Ω resistors and (b) the voltage drop across the 10-Ω resistor.

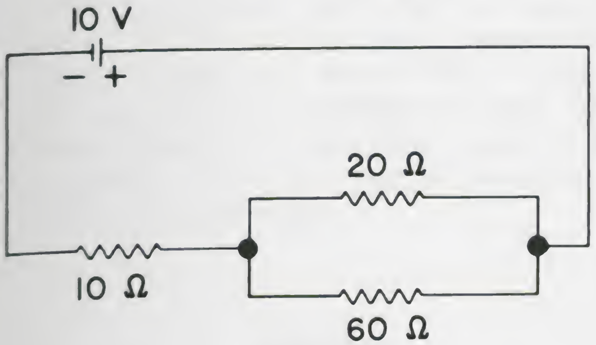


Figure 46.

7. Figure 47 shows voltage and current for two devices, *a* and *b*. Which one is ohmic? What is its resistance?

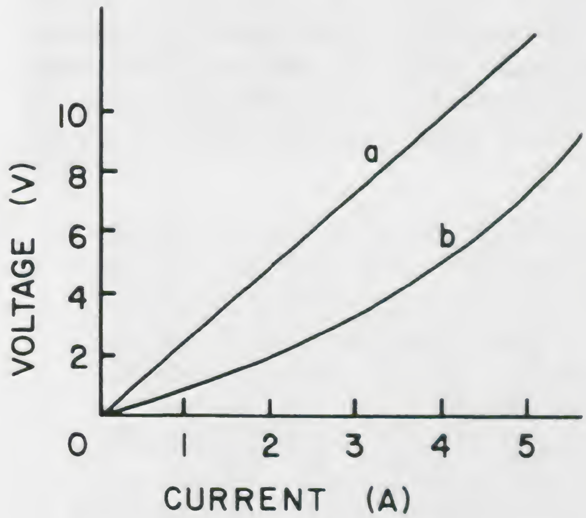


Figure 47.

SECTION C

In Experiment A-1 you studied some circuits which could be used to change the ranges of ammeters and voltmeters. The fact that the range of an ammeter can be extended by placing a suitable resistor called a *shunt* in *parallel* with the meter was discussed briefly. Similarly, you saw that the range of a voltmeter can be extended by placing a suitable resistor called a *multiplier* in *series* with the meter. Conversions of ammeter and voltmeter ranges by means of shunts and multipliers have great practical value. An ammeter which can read from 0-50 μA and also from 0-5 mA by selection of the proper shunt is often more useful than a meter which can read only on one of these ranges. How to provide an effective choice of ranges (including resistance ranges) is an important design feature of any multimeter.

In the next two experiments you will learn how to select ammeter shunts and voltmeter multipliers for the purpose of converting the range of a given meter movement.

In the third and final experiment you will study how a meter affects the circuit in which it is used.

EXPERIMENT C-1. Ammeter Shunt

The SRM-100, which is supplied as part of the multimeter kit and which you have used in previous experiments, has a basic range of 0-100 μA. By using suitable plug-in units to serve as shunts, you were able to obtain four additional current ranges. Table II lists these current ranges together with the resistance values of the shunts.

Notice that larger current ranges are obtained by using smaller values of shunt resistance. Does this make sense? You might look at it this way: the smaller the shunt resistance, the greater its short-circuiting effect on the meter itself. That is, a greater portion of the incoming current bypasses the meter through the shunt. Then a larger incoming current is necessary to obtain full-scale deflection of the meter under these conditions. The upper limit of the current range is therefore higher.

TABLE II

Current Range	Shunt Resistance
0 to 500 mA	0.2 Ω
0 to 50 mA	2 Ω
0 to 5 mA	20.4 Ω
0 to 0.5 mA	250 Ω

In this experiment you are provided with a 100-μA meter of known meter resistance R_m = 1 kΩ. Your problem is to find the parallel, or shunt, resistance R_p that will convert the meter to a milliammeter which reads 100 mA for full-scale deflection. In other words, you are asked to increase the range of the meter by a factor of 1000. Notice, incidentally, that you can use the same scale on the meter for each of these ranges if you multiply the meter reading by the appropriate number.

Procedure

1. Wire the circuit shown in Figure 48. The ammeter which is to be converted is denoted by X. For the purpose of this experiment, the shunt resistance R_p consists of a length of nichrome wire (use the mounted nichrome wire of Experiment B-1). A lead with a banana plug or spade lug at the end serves adequately as a sliding contact to the nichrome wire.

2. Turn up the power supply until the current through ammeter A is 100 mA. Connect the sliding contact from ammeter X to the nichrome wire near point a and slide the contact toward b until ammeter X also reaches full-scale deflection. Measure the length of nichrome wire from a to c. This is the length ac required to make up the required shunt resistance R_p.

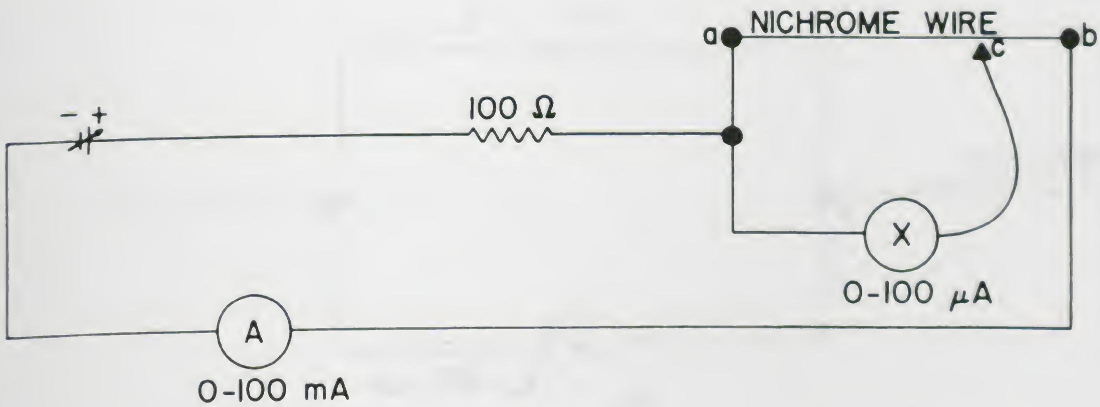


Figure 48.

3. In Experiment B-1 you observed that the voltage drop along a length of wire is proportional to the length. Since the voltage drop V is equal to the current I times the resistance R, the shunt resistance R_p is proportional to the length *ac* of wire. Ask your instructor for the resistance per meter of the wire you are using. From this information, you can calculate the required shunt resistance, R_p.

Discussion

Compare the shunt resistance R_p which you determined experimentally with the resistance R_m of the meter that you used. (This is 1 kΩ.) Ammeter shunt resistances are smaller than the resistance R_m of the meter movement itself. To increase the meter range by a factor of 10^3, how many times smaller must R_p be than R_m? A hundred times smaller? A thousand?

It turns out that an increase in meter range by a factor of 10^3 requires a shunt resistance R_p which is smaller than the meter resistance R_m by approximately the same factor. Why this is so can be understood if you study the physics of the problem. We can break the problem down into steps:

1. The first step is to write down the problem. In this case, you are to convert a 100-μA ammeter to a 100-mA ammeter. In other words, you should increase the ammeter range by a factor $n = 10^3$.

2. Draw a circuit diagram as in Figure 49. I is the total current, I_p and I_m are the branch currents.

3. Since voltage drops across resistors in parallel are equal, we can write

$$\text{Voltage drop} = I_m R_m = I_p R_p$$

Solving for the shunt resistance R_p,

$$R_p = \frac{I_m R_m}{I_p} \tag{4}$$

Since the total current into point *a* equals the total current leaving point *a*,

$$I = I_m + I_p$$

or

$$I_p = I - I_m \tag{5}$$

Use Equation (5) to eliminate the shunt current I_p from Equation (4).

$$R_p = \frac{I_m R_m}{I - I_m} \tag{6}$$

This can also be written as

$$R_p = \frac{R_m}{(I/I_m) - 1} \tag{7}$$

And, since $I = nI_m$, where n is the range factor,

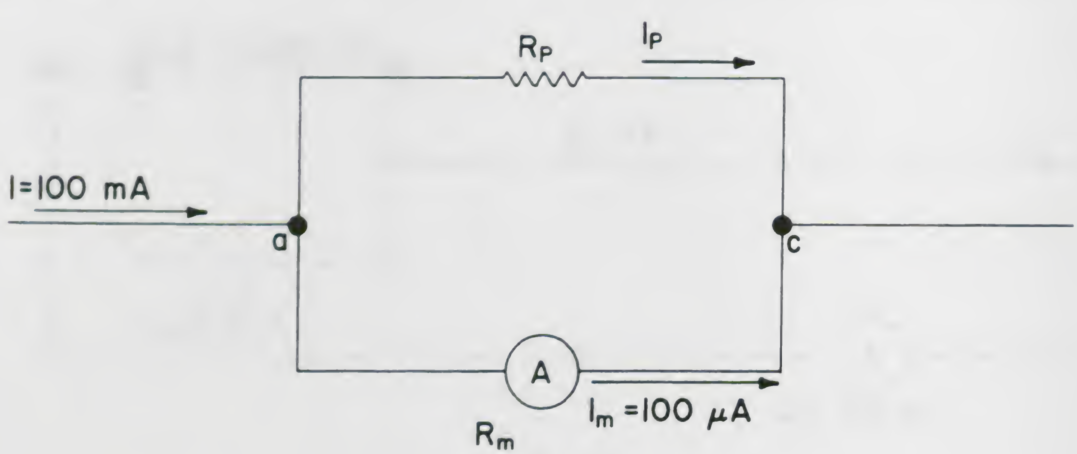


Figure 49.

$$R_p = \frac{R_m}{n - 1} \tag{8}$$

4. We can now substitute known numerical values into Equation (8). The value of the meter resistance R_m is known (1 kΩ). The current I (= 100 mA) is the total current which, flowing into the parallel system, will produce full-scale deflection of the meter. So, I_m = 100 μA. The ratio of the currents is

$$n = \frac{I}{I_m} = \frac{100 \text{ mA}}{100\ \mu\text{A}} = \frac{100 \times 10^{-3} \text{ A}}{100 \times 10^{-6} \text{ A}} = 10^3$$

Using $n = 10^3$ in Equation (8), the value of the required shunt resistance is

$$R_p = \frac{R_m}{999}\ \Omega$$

The formula shows the relations between R_p and R_m for any value of n. You can see that R_p is about 1000 times smaller than R_m in this case.

In practice, if you wish to change the range of an ammeter, use Equation (8) to do the necessary computation before doing the experiment. Then you will know in advance what shunt resistance to use.

EXPERIMENT C-2. Voltmeter Series Resistance or Multiplier

You have used the 0 to 100-μA instrument in previous experiments as a voltmeter by connecting it in series with one of three resistors or multipliers mounted on a plug-in unit. The multipliers are labeled according to voltage ranges as follows:

TABLE III

Voltage Range	Multiplier Resistance
0 to 0.5 V	4 kΩ
0 to 5 V	49 kΩ
0 to 15 V	149 kΩ

The respective resistance values are given for reference. The series resistors serve two purposes: 1. they allow the ammeter to be used as a voltmeter, and 2. they determine the measuring ranges of the voltmeter. While the deflection of the pointer is caused by current through the meter, the label on the series resistor plug-in unit permits you to read that deflection in terms of the voltage across the terminals of the meter.

To obtain higher voltage ranges, higher values of resistance must be used in series with the meter. Higher values are necessary because the increased portion of the voltage drop must occur across the series resistance. The maximum voltage drop across the meter movement is fixed, and it is determined by the maximum current the meter can stand.

To do this experiment you can use the 100-μA meter (SRM-100) with the 0 to 0.5-V plug-in unit. Together they form the voltmeter (labeled X in Figure 50), which reads 0.5 V for full-scale deflection. The meter resistance R_m in this case is the sum of the resistance of the meter itself (1 kΩ) plus the resistance of the plug-in unit (4 kΩ). Your problem is to find the (additional) series resistance R_s needed to convert the voltmeter range to read 5 V full-scale. In other words, you are asked to increase the range of the voltmeter X by a factor of ten.

Procedure

1. Wire the circuit shown in Figure 50. For R_S use an appropriate number of resistors in series or a suitable *decade resistance* box, if available. A decade resistance box contains a collection of resistors, combinations of which can be selected by means of selector switches. To prevent the voltmeter from being damaged by too much current, begin with a large value for R_S, *at least* 100 kΩ.

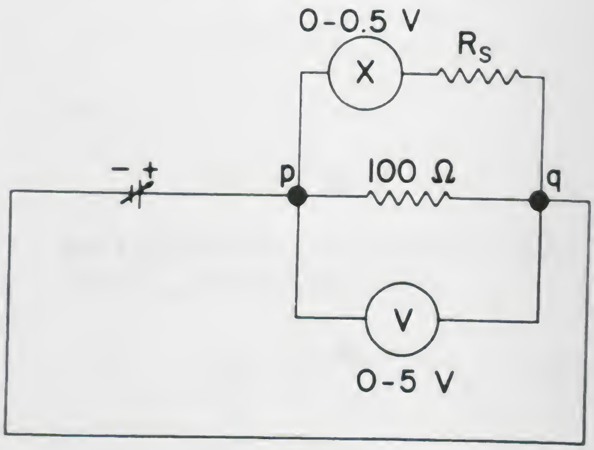


Figure 50.

2. Turn up the power supply voltage until the calibrated 0-5 V voltmeter reads 5 V. Now reduce R_S in small steps to increase deflection of voltmeter X until it also reads full-scale. Record this value of R_S. This is the series resistance, or multiplier, needed to convert the voltmeter range from 0-0.5 V to 0-5 V.

Voltmeter series resistances are high compared with the resistance R_m of the meter movement itself. Did you notice that a series resistance nearly ten times as large as the resistance of the meter movement is needed to increase the voltmeter range by a factor of ten? (Note that in this case the "resistance of the meter movement" includes the actual 1-kΩ resistance of the movement *plus* the 4-kΩ plug-in unit which is being used as part of the movement.) As before, we can study

the physics of the problem, proceeding step by step.

1. The problem is to convert a 0.5-V voltmeter to a 5.0-V voltmeter. In other words you need to increase the voltmeter range by a factor of $n = 10$.

2. Draw the circuit diagram as shown in Figure 51.

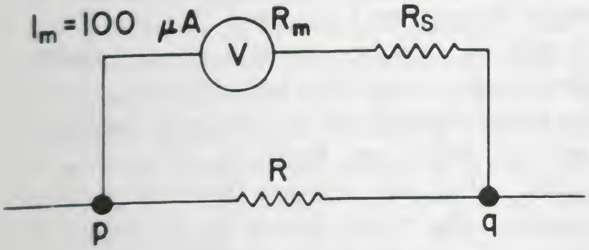


Figure 51.

3. The total voltage drop (V_{pq}) across the combination of the meter and its multiplier resistance (R_s) is equal to the sum of the individual voltage drops across the meter (V_m) and the series resistance (V_s). That is

$$V_{pq} = V_m + V_s$$

Since $V_m = I_m R_m$ and $V_s = I_m R_s$,

$$V_{pq} = I_m R_m + I_m R_s \tag{9}$$

We can solve this for the series resistance R_s to get

$$R_s = \frac{V_{pq}}{I_m} - R_m \tag{10}$$

or, writing it another way,

$$\begin{aligned} R_s &= R_m\left(\frac{V_{pq}}{I_m R_m} - 1\right) \\ &= R_m\left(\frac{V_{pq}}{V_m} - 1\right) \end{aligned} \tag{11}$$

Since $V_{pq}/V_m = n$, we can write

$$R_s = R_m(n - 1) \tag{12}$$

4. Now we can substitute numerical values into Equation (12). In this case, the voltage (V_{pq}) across the series combination $R_m + R_s$ which produces full-scale deflection of the meter is 5 V. When $V_{pq} = 5$ V, $I_m = 100\ \mu$A.

The ratio of voltages $V_{pq}/V_m = 5\text{ V}/0.5\text{ V} = 10$ is the factor n by which the range of the meter is to be increased.

Since $R_s = R_m\ (n - 1)$ (12)

and $n = 10$

$$R_s = 9\ R_m$$

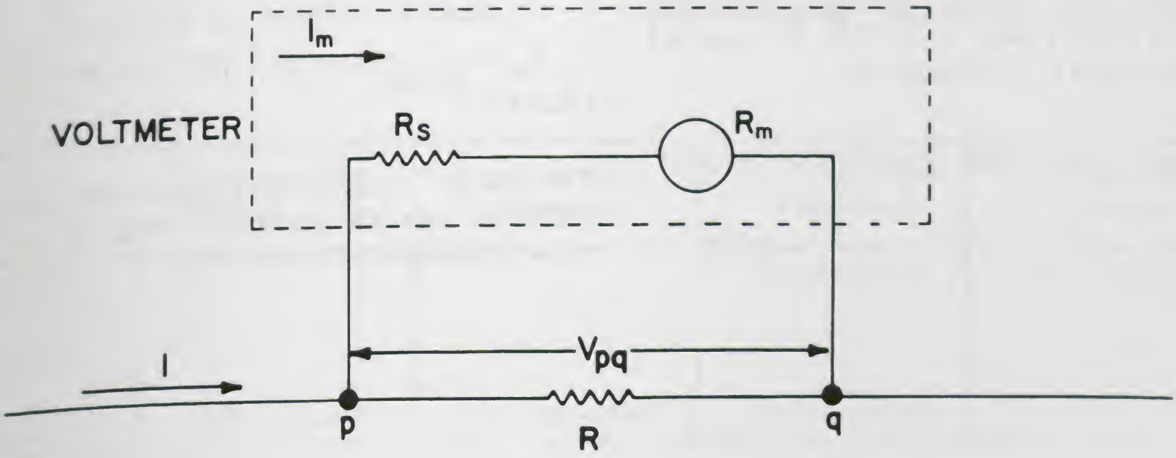


Figure 52.

Equation (12) shows the relation between R_s and R_m for any value of n. Now you can see why R_s is nearly n times larger than R_m (remember, R_m is the sum of the resistances of the meter movement and the [0-0.5 V] plug-in unit).

Sensitivity Rating

In the next experiment you will be given two voltmeters which have very different *sensitivity ratings*. The sensitivity rating tells us the internal resistance of the meter. This is the resistance automatically placed in parallel with the circuit element whose voltage is being measured when we connect the meter. Rather than give a table of resistances, one for each scale of the meter, the sensitivity rating is written as a single number from which the resistances of all of the scales of a given meter can be calculated. We write the sensitivity rating in units of ohms per volt (Ω/V). The resistance of each scale is obtained by multiplying the sensitivity rating of the meter by the full-scale voltage of that scale. For example, a 1-kΩ/V instrument set on a 1-V scale introduces a resistance of 1 kΩ; on the 10-V scale, the internal resistance is 10 kΩ. As you will see later, the higher the resistance of the voltmeter, the less it will disturb the circuit being measured.

Example 9. Suppose you switch from a 1-V scale to a 25-V scale on a 2-kΩ/V instrument. Determine the new internal resistance of the meter.

Solution. The internal resistance corresponding to the 1-V scale is 2000 Ω. The internal resistance on the 25-V scale is

$$\text{Rating} \times \text{scale} = 2000\ \frac{\Omega}{\text{V}} \times 25\ \text{V} = 50{,}000\ \Omega$$

$$= 50\ \text{k}\Omega$$

Another way of looking at the sensitivity rating is as follows. It represents the amount of series resistance (multiplier) needed to produce full-scale meter deflection for one volt. Sensitivity rating (Ω/V) is a convenient quantity to work with because it is constant for a given voltmeter. *To find the actual resistance of the meter, you multiply this constant (Ω/V) by the volts scale that you wish to use.*

The sensitivity rating of a voltmeter is related to the meter current I_m which is needed to produce full-scale deflection. From Example 8, you can see that the sensitivity rating is just equal to the internal resistance of the meter divided by the full-scale voltage. Looking back to Equation (9), $V_{pq} = I_m(R_m + R_s)$, you can see that the internal resistance, $R_m + R_s$, divided by the full-scale voltage V_{pq}, which is the sensitivity rating of the meter, is just equal to the reciprocal of the full-scale meter current:

$$\frac{R_m + R_s}{V_{pq}}\ \frac{\Omega}{\text{V}} = \frac{1}{I_m}$$

Example 10. The sensitivity of a voltmeter is 20,000 Ω/V. Find the meter current needed to produce full-scale deflection.

Solution.

$$20{,}000\ \frac{\Omega}{\text{V}} = \frac{1}{I_m}$$

$$I_m = \frac{1}{20{,}000}\ \text{A} = 50 \times 10^{-6}\ \text{A} = 50\ \mu\text{A}$$

The current required to produce full-scale deflection and the sensitivity rating of the meter are *reciprocal* to each other.

EXPERIMENT C-3. Meter Loading

In this experiment, you will observe and compare the effects on circuit measurements of voltmeters having different sensitivity ratings.

Procedure

1. Wire a circuit consisting of a DC-power supply, two 10-kΩ resistors, a 0 to 0.5-mA ammeter, and a 0 to 15-V voltmeter, as shown in Figure 53. The 0 to 5-V low-sensitivity voltmeter will be connected later. Get the sensitivity of each meter, either by reading it from the meter itself or by getting it from your teacher. The meters we have used have sensitivities of 10 kΩ/V and 2 kΩ/V, and we have called them V_{Hi} and V_{Lo}, respectively. Label your two voltmeters in like manner.

2. Turn up the power supply until V_{Hi} displays 6 V on *open circuit*. Do this by disconnecting the circuit at one end of a 10-kΩ resistor. Then reconnect the circuit and measure the current and voltage. Record these values in column 1 of Table IV.

3. Connect V_{Hi} across resistance R_1 and again measure current and voltage. Record your measured values in column 2 of Table IV.

4. Disconnect the voltmeter V_{Hi}. Measure the current and record it in column 3.

5. Finally, connect the low-sensitivity voltmeter V_{Lo} across R_1 and record the current and voltmeter readings in column 4.

Discussion

When the low-sensitivity voltmeter V_{Lo} is connected to the circuit, current and voltage readings change considerably. If you used the circuit values suggested in Figure 53, you probably found that the current increased from about 0.3 mA to 0.4 mA, and the voltage measured across R_1 decreased from 3 V to 2 V. These sizeable changes amount to about 33% of the original values. They should not be ignored. Can you account for the changes you observed in the meter readings? Before actually analyzing your data, think about how connecting a meter to a circuit can affect the values of current and voltage.

The internal resistance of the meter includes the resistance of the meter movement and any shunt or series resistance associated with the meter. When the meter is connected to a circuit, its internal resistance becomes part of the circuit. Therefore, the meter always disturbs the original circuit. The internal resistance of an ammeter is connected in series with the resistance of the circuit. Thus it increases the overall circuit resistance and reduces the current. The internal resistance of a voltmeter is connected in parallel to the resistance across which the voltage is being measured. This reduces the overall

TABLE IV

	V_{Hi} Connected Across $R_1 + R_2$	V_{Hi} Connected Across R_1	No Voltmeters Connected	V_{Lo} Connected Across R_1
V_{Hi} (V)			not connected	not connected
I (mA)				
V_{Lo} (V)	not connected	not connected	not connected	

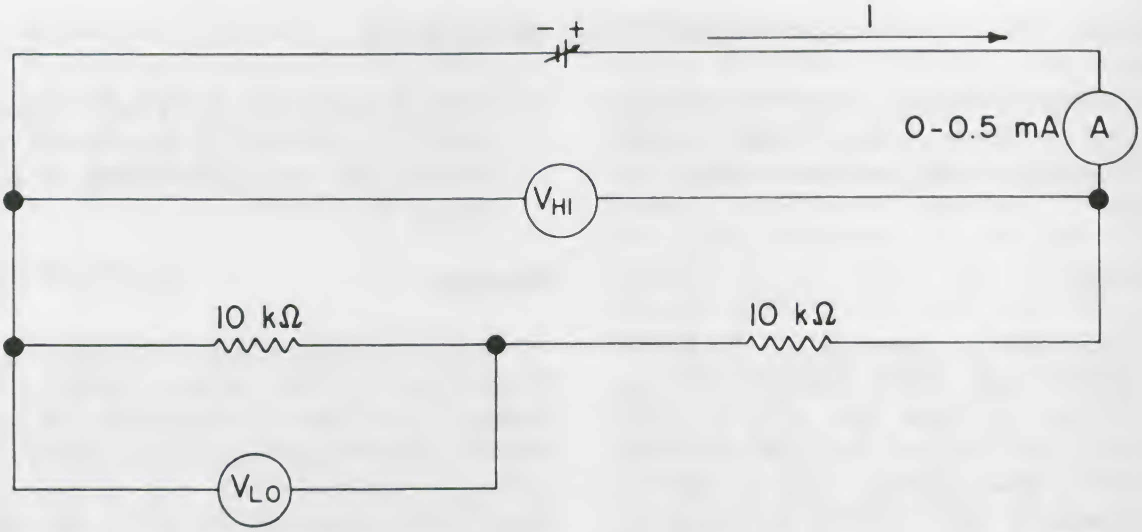


Figure 53.

circuit resistance and correspondingly increases the current. The act of making a measurement always disturbs the original circuit and thus changes the current. While it is impossible to eliminate these changes, we can certainly try to minimize them.

Fortunately, we seldom have to worry about the effects of connecting an ammeter. In most practical applications the internal resistance of an ammeter is so small compared with the resistance of the circuit itself that it causes negligible changes in current.

For example, consider a circuit carrying a current in the milliampere range. The voltage source might be a few volts, say 10 V, and the circuit resistance might be about 1000 Ω. In that case the current is 10 mA. A typical 0-50 mA ammeter has an internal resistance $r = 5\ \Omega$. When the meter is connected to the circuit, as shown in Figure 54, the equivalent series resistance is

$$R + r = 1000\ \Omega + 5\ \Omega = 1005\ \Omega$$

The current changes to

$$I = \frac{10\ \text{V}}{1005\ \Omega} = 9.95\ \text{mA}$$

The percent change in current is thus only

$$\frac{0.05\ \text{mA}}{10\ \text{mA}} \times 100 = 0.5\%$$

This change is so small that it probably cannot be detected by the meter. Thus placing a milliammeter in the circuit has a negligible effect on the current if its internal resistance r is small compared with the total circuit resistance R.

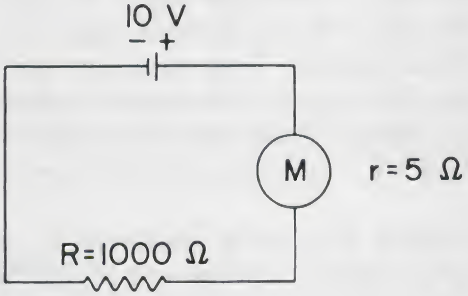


Figure 54.

When we connect a voltmeter to a circuit, the story is a little different. The voltmeter provides a parallel path along which current can flow. When the internal resistance of the voltmeter is comparable in size to the circuit resistance across which the voltage drop is measured, or even smaller, the overall resistance of the circuit is lowered by a significant amount. A larger current is drawn from the voltage source than is the case when the meter is not connected. We say that the meter *loads* the circuit. Under such conditions both ammeter and voltmeter readings are misleading. They do not reflect the values of

current and voltage which exist when the meter is not connected.

On the other hand, if the voltmeter's internal resistance is very high compared to the resistance of the circuit portion under test, not much current is drawn by the meter. In this case, circuit loading is negligible. In general, the smaller the loading effect, the better the measurement.

To picture this another way, we can use the analogy between the flow of electric current and that of water in a pipe. Negligible circuit loading corresponds to the restricted flow of water through a parallel pipe of narrow diameter, as shown in Figure 55A. The current through the small pipe is small enough so that the total current in the circuit is not much changed. Heavy circuit loading corresponds to the case of water being drawn into a parallel pipe of wide diameter as shown in Figure 55B. The relatively large amount of water diverted through the meter significantly reduces the original current.

To obtain a reliable voltage measurement, the internal resistance of the voltmeter must be much higher than the resistance of the circuit portion being tested.

Now return to the data which you tabulated in Experiment C-3 and analyze the results. In particular, try to account for the changes in meter readings in a mathematical way. You will need to apply the physics you learned in previous experiments to do the calculations. The following step-by-step procedure might be helpful:

1. Use the known voltmeter-sensitivity ratings and voltage scales to compute the internal resistances of the meters V_{Hi} and V_{Lo}.

2. Use the internal resistance of meter V_{Hi} to compute the equivalent resistance of the circuit when V_{Hi} is connected across (a) the series combination $R_1 + R_2$, and (b) R_1 alone.

3. Use Ohm's Law to calculate the current I for both cases.

4. Use Ohm's Law to calculate the current I when neither voltmeter is connected. The resistance is $R_1 + R_2$ and the voltage is the open-circuit voltage of the power supply (6 V). You should now have three calculated values of the current. Compare these with the three corresponding experimental values of current recorded in Table IV.

5. Use the internal resistance of the low-sensitivity meter V_{Lo} to compute the equivalent resistance of the circuit when V_{Lo} is connected across R_1.

6. Use Ohm's Law to calculate the current I for this case. Compare the calculated value of I with the corresponding experimental value recorded in Table IV.

7. Complete the analysis by calculating the actual voltages across R_1 and $R_1 + R_2$ for each of the voltage measurements. How do they compare with the measured values? Can you explain why V_{Lo} has a much more serious loading effect on the circuit than V_{Hi}?

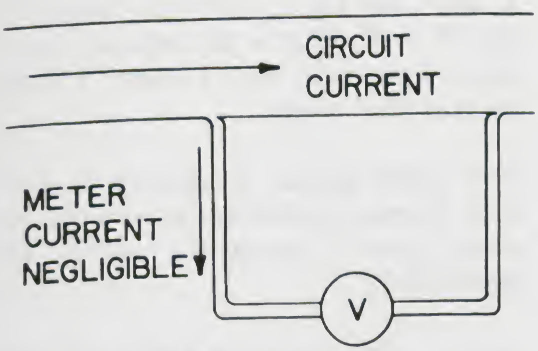


Figure 55A. A water-flow analogy to voltmeter circuit loading.

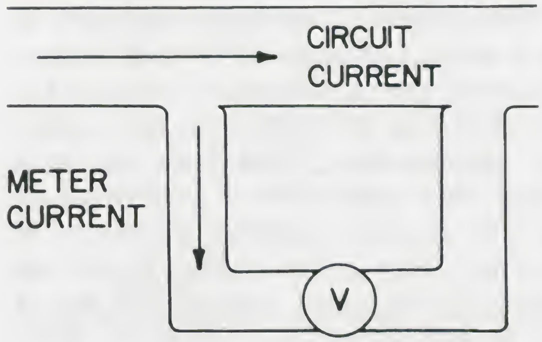


Figure 55B.

The purpose of doing this analysis is to gain a better understanding of what happens in a circuit when a voltmeter is connected to it. In all of your calculations you have applied basic physical laws. These laws are useful because they enable you to *predict results*. Any time you use a voltmeter, you should be concerned about meter loading. If you can compute the expected changes, you will be able to correct for the effects of meter loading.

SUMMARY

The *range of an ammeter* can be changed by means of a *shunt*, a resistor placed in parallel with the meter movement. The lower the resistance of the shunt, the higher is the range of the meter. The required value for the shunt resistance, R_p, is calculated to be

$$R_p = \frac{R_m}{(I/I_m) - 1}$$

where R_m is the resistance of the meter movement, I is the maximum current desired for the specified range, and I_m is the actual current needed in the meter movement to produce full-scale deflection.

The *range of a voltmeter* is changed by means of a *multiplier*, a resistor placed in series with the meter movement. The higher the resistance of the multiplier, the higher the range of the voltmeter. The required value for the multiplier resistance, R_s, is computed to be

$$R_s = \frac{V}{I_m} - R_m$$

where V is the specified voltage range, I_m is the current required for full-scale deflection of the meter movement, and R_m is the resistance of the meter movement.

Meter loading of a circuit exists when the meters used for measurements significantly affect the circuit. The *internal resistance* of a meter determines how much it will load a circuit.

The *sensitivity rating* for a voltmeter is a convenient measure of its internal resistance. It is expressed in units of ohms-per-volt (Ω/V). To calculate the actual internal resistance, multiply the sensitivity rating by the full-scale voltage on the range in use. The sensitivity rating is determined by the current required to produce full-scale deflection of the meter movement.

To avoid a significant effect on a circuit when measuring voltage, the resistance of the voltmeter must be much greater than the resistance of circuit elements being tested.

In most practical applications, the internal resistance of an ammeter is very small in comparison with the resistance of the rest of the circuit. Therefore its effect on the circuit usually is not significant.

PROBLEMS

1. A meter movement has an internal resistance of 100 Ω and requires 200 μA to produce full-scale deflection.

    a. Calculate the required shunt resistance to produce a 0 to 1-mA meter.
    b. Do the same for a 0 to 1-A meter.

2. For the meter movement described in Problem 1, what series resistance would be required to produce a 0 to 10-V voltmeter?

3. If the meter movement described in Problem 1 is used in a voltmeter, what will the sensitivity rating be?

4. A voltmeter has a sensitivity rating of 40,000 Ω/V. What is the internal resistance of the meter when reading 25 V on the 0 to 50-V range?

5. How much current is required to produce full-scale deflection in a voltmeter which has a sensitivity rating of 40,000 Ω/V?

6. In the circuits shown in Figure 56, the

ammeter has an internal resistance of 200 Ω and the voltmeter has a resistance of 20 kΩ. Calculate the meter readings for each circuit.

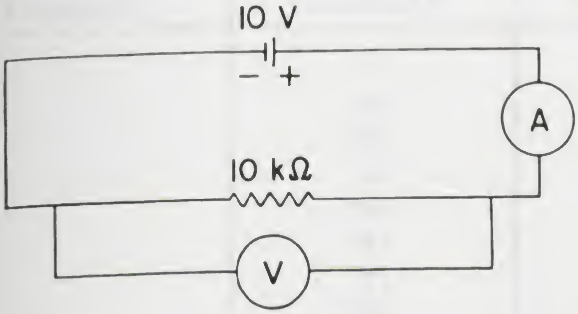


Figure 56A.

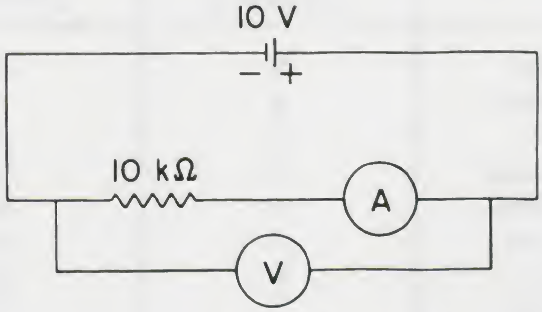
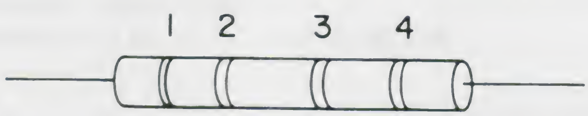


Figure 56B.

APPENDIX: RESISTOR COLOR CODE

Color	1st Band (1st Digit)	2nd Band (2nd Digit)	3rd Band (Multiplier)	4th Band (Tolerance)
Black	0	0	1	
Brown	1	1	10	
Red	2	2	10^2	
Orange	3	3	10^3	
Yellow	4	4	10^4	
Green	5	5	10^5	
Blue	6	6	10^6	
Violet	7	7	10^7	
Gray	8	8	10^8	
White	9	9	10^9	
Gold	–	–	10^{-1}	5%
Silver	–	–	10^{-2}	10%
None	–	–	–	20%



Examples:

1st Band	2nd Band	3rd Band	4th Band	Resistance
orange	orange	brown	gold	330 Ω ± 5%
yellow	violet	orange	silver	47 kΩ ± 10%
brown	green	blue	silver	15 MΩ ± 10%
gray	red	red		8200 Ω ± 20%
orange	white	gold	gold	3.9 Ω ± 5%